LC Precision in the MSSM

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1. The Grand Scheme
2. Renormalizing the MSSM
3. Results for the MSSM Higgs at the LC
4. Results for Dark Matter at the LC
5. Conclusions

1. The Grand Scheme

The LHC up and running . . .
→ discovery of BSM physics in 2015?

The ILC is still coming . . .
. . . a bit later than anticipated
→ to investigate BSM physics

⇒ New Physics is certainly around the corner

⇒ Time to get ready for BSM physics

The big question:

Which Lagrangian describes the world?

My guess:

It is a supersymmetric one

$\Rightarrow$ concentrate on the (N)MSSM from now on

(other people $\Rightarrow$ other guesses $\Rightarrow$ other priorities . . .)

In any case:

$\Rightarrow$ we have to measure as many observables as possible

– masses
– branching ratios
– angular distributions
– cross sections
– . . .

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In any case:

$\Rightarrow$ we have to measure as many observables as possible

– masses
– branching ratios
– angular distributions
– cross sections
– . . .

$\Rightarrow$ compare with theory calculations at the same level of accuracy

The Minimal Supersymmetric Standard Model (MSSM)

Superpartners for Standard Model particles

$$\left[u, d, c, s, t, b\right]_{L,R} \quad \left[e, \mu, \tau\right]_{L,R} \quad \left[\nu_{e,\mu,\tau}\right]_{L} \qquad \text{Spin } \tfrac{1}{2}$$

$$\left[\tilde{u}, \tilde{d}, \tilde{c}, \tilde{s}, \tilde{t}, \tilde{b}\right]_{L,R} \quad \left[\tilde{e}, \tilde{\mu}, \tilde{\tau}\right]_{L,R} \quad \left[\tilde{\nu}_{e,\mu,\tau}\right]_{L} \qquad \text{Spin } 0$$

$$g \quad \underbrace{W^{\pm}, H^{\pm}} \quad \underbrace{\gamma, Z, H_1^0, H_2^0} \qquad \text{Spin 1 / Spin 0}$$

$$\tilde{g} \quad \tilde{\chi}^{\pm}_{1,2} \quad \tilde{\chi}^{0}_{1,2,3,4} \qquad \text{Spin } \frac{1}{2}$$

Enlarged Higgs sector: Two Higgs doublets $\Leftarrow$ for obvious reasons some focus here!

Problem in the MSSM: many scales

Problem in the MSSM: complex phases

Where are we? (a selection!)

1. Neutral Higgs boson masses
   – $\mathcal{O}(\alpha_t\alpha_s)$ in the cMSSM [S.H., W. Hollik, H. Rzehak, G. Weiglein '07]
   – $\mathcal{O}\left(\alpha_t\alpha_s^2\right)$, $\mathcal{O}\left(\alpha_t^2\alpha_s\right)$, rMSSM [S. Martin '07]
   – $\mathcal{O}\left(\alpha_t\alpha_s^2\right)$, rMSSM (incl. fin. terms) [Haarlander, Kant, Mihaila, Steinhauser '08]
2. Charged Higgs mass
   – full 1-loop [M. Frank et al. '06]
   – $\mathcal{O}(\alpha_t\alpha_s)$ [M. Frank et al. '13]
3. Production cross sections at the LC
   – $e^+e^- \to Z/A\,h/H$, at one-loooop, rMSSM [S.H., Hollik, Rosiek, Weiglein '01]
   – $e^+e^- \to H^\pm e^\mp \nu$ at one-loop, rMSSM [O. Brein, T. Figy '07][T. Farris et al. '04]
   – Z-factors at 2-loop [M. Frank, T. Hahn, S.H., W. Hollik, H. Rzehak, G. Weiglein '06]
4. Higgs decays
   – full 1-loop (depending on final state) [. . .]
   – Z-factors at 2-loop [M. Frank, T. Hahn, S.H., W. Hollik, H. Rzehak, G. Weiglein '06]
5. Decays to Higgs bosons
   – (partial) 1-loop, rMSSM [. . .]
   – (partial) 1-loop, cMSSM [H. Rzehak, G. Weiglein, K. Williams]
     [A. Bharucha, T. Fritzsche, S.H., F. v.d. Pahlen, H. Rzehak, C. Schappacer '11 - '13]

What is missing? (a selection!)

1. Neutral Higgs boson masses
   – full 2-loop
   – more 3-loop (and in "easier accessible" scheme?)
   – leading 4-loop
   – LL, NLL, . . . resummation

2. Charged Higgs boson mass
   – leading 2-loop

3. Higgs decays
   – full 1-loop in the r/cMSSM (some final states)
   – leading 2-loop

4. Decays to Higgs bosons
   – full 1-loop in the rMSSM (some initial states)
   – full 1-loop in the cMSSM (some initial states)

⇒ provide corresponding codes!

2. Renormalization of the cMSSM

Generic problems for SUSY loop calculations:

- SUSY has to be preserved in the calculation
- Many different mass scales
- Many more mass scales than free parameters
- Even more parameters: mixing angles, complex phases
- Renormalization is much more involved than in the SM
  - much less explored than in the SM
  - has to preserve/respect mass relations
  - depend on mass scales realized in Nature
  - sometimes no really good solution exist (e.g. $\tan\beta$)
  - many sectors enter at the same time

  $\Rightarrow$ this is the biggest issue!

Enlarged Higgs sector: Two Higgs doublets

$$H_1 = \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1 + i\chi_1)/\sqrt{2} \\ \phi_1^- \end{pmatrix}$$

$$H_2 = \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2 + i\chi_2)/\sqrt{2} \end{pmatrix}$$

$$V = m_1^2 H_1 \bar{H}_1 + m_2^2 H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.})$$

$$+ \underbrace{\frac{g'^2 + g^2}{8}}(H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \underbrace{\frac{g^2}{2}} |H_1 \bar{H}_2|^2$$

gauge couplings, in contrast to SM

physical states: $h^0, H^0, A^0, H^\pm$

Goldstone bosons: $G^0, G^\pm$

Input parameters: (to be determined experimentally)

$$\tan\beta = \frac{v_2}{v_1}, \qquad M_A^2 = -m_{12}^2 (\tan\beta + \cot\beta)$$

Enlarged Higgs sector: Two Higgs doublets with $\mathcal{CP}$ violation

$$H_1 = \begin{pmatrix} H_1^1 \\ H_1^2 \end{pmatrix} = \begin{pmatrix} v_1 + (\phi_1 + i\chi_1)/\sqrt{2} \\ \phi_1^- \end{pmatrix}$$

$$H_2 = \begin{pmatrix} H_2^1 \\ H_2^2 \end{pmatrix} = \begin{pmatrix} \phi_2^+ \\ v_2 + (\phi_2 + i\chi_2)/\sqrt{2} \end{pmatrix} e^{i\xi}$$

$$V = m_1^2 H_1 \bar{H}_1 + m_2^2 H_2 \bar{H}_2 - m_{12}^2 (\epsilon_{ab} H_1^a H_2^b + \text{h.c.})$$

$$+ \underbrace{\frac{g'^2 + g^2}{8}}(H_1 \bar{H}_1 - H_2 \bar{H}_2)^2 + \underbrace{\frac{g^2}{2}} |H_1 \bar{H}_2|^2$$

gauge couplings, in contrast to SM

physical states: $h^0, H^0, A^0, H^\pm$

2 $\mathcal{CP}$-violating phases: ξ, arg(m_{12}) $\Rightarrow$ can be set/rotated to zero

Input parameters: (to be determined experimentally)

$$\tan\beta = \frac{v_2}{v_1}, \qquad M_{H^\pm}^2$$

The Higgs sector of the cMSSM at tree-level:

- phase of m_{12} :

  $m_{12} = 0$ and $\mu = 0 \Rightarrow$ additional $U(1)$ (PQ) symmetry

  reality: $m_{12} \neq 0$, $\mu \neq 0$

  $\Rightarrow$ perform PQ transformation with $\phi_{\rm PQ}$

$$\begin{aligned} m_{12}^{2\prime} &= |m_{12}^2| e^{i(\phi_{m_{12}} - \phi_{\rm PQ})} \\ \mu' &= |\mu| e^{i(\phi_\mu - \phi_{\rm PQ})} \end{aligned}$$

  $\Rightarrow$ m_{12} can always be chosen real

- phase of H_2: ξ :

  mixing between $\mathcal{CP}$-even and $\mathcal{CP}$-odd states:

$$\mathcal{M}_{\mathcal{CP}-\text{even},\mathcal{CP}-\text{odd}} = \begin{pmatrix} 0 & m_{12}^2 \sin\xi \\ -m_{12}^2 \sin\xi & 0 \end{pmatrix}$$

  Tadpoles have to vanish: $T_A^{\rm tree} \propto \sin\xi \, m_{12}^2 \stackrel{!}{=} 0$
  $\Rightarrow \xi = 0 \Rightarrow$ no $\mathcal{CP}$V at tree-level

The Higgs sector of the cMSSM at the loop-level:

Complex parameters enter via loop corrections:

– μ : Higgsino mass parameter

– $A_{t,b,\tau}$: trilinear couplings $\Rightarrow X_{t,b,\tau} = A_{t,b,\tau} - \mu^* \{\cot\beta, \tan\beta\}$ complex

– $M_{1,2}$: gaugino mass parameter (one phase can be eliminated)

– M_3 : gluino mass parameter

$\Rightarrow$ can induce $\mathcal{CP}$-violating effects

Result:

$$(A, H, h) \rightarrow (h_3, h_2, h_1)$$

with

$$m_{h_3} > m_{h_2} > m_{h_1}$$

$\Rightarrow$ strong changes in Higgs couplings to SM gauge bosons and fermions

$\tilde{t}/\tilde{b}$ sector of the MSSM: (scalar partner of the top/bottom quark)

Stop, sbottom mass matrices ($X_t = A_t - \mu^*/\tan\beta$, $X_b = A_b - \mu^* \tan\beta$):

$$\mathcal{M}^2_{\tilde{t}} = \begin{pmatrix} M^2_{\tilde{t}_L} + m_t^2 + DT_{t_1} & m_t X_t^* \\ m_t X_t & M^2_{\tilde{t}_R} + m_t^2 + DT_{t_2} \end{pmatrix} \xrightarrow{\theta_{\tilde{t}}} \begin{pmatrix} m^2_{\tilde{t}_1} & 0 \\ 0 & m^2_{\tilde{t}_2} \end{pmatrix}$$

$$\mathcal{M}^2_{\tilde{b}} = \begin{pmatrix} M^2_{\tilde{b}_L} + m_b^2 + DT_{b_1} & m_b X_b^* \\ m_b X_b & M^2_{\tilde{b}_R} + m_b^2 + DT_{b_2} \end{pmatrix} \xrightarrow{\theta_{\tilde{b}}} \begin{pmatrix} m^2_{\tilde{b}_1} & 0 \\ 0 & m^2_{\tilde{b}_2} \end{pmatrix}$$

mixing important in stop sector (also in sbottom sector for large $\tan\beta$)

soft SUSY-breaking parameters A_t, A_b also appear in ϕ-$\tilde{t}/\tilde{b}$ couplings

$$m^2_{\tilde{t}_{1,2}} = m_t^2 + \frac{1}{2}\left(M^2_{\tilde{t}_L} + M^2_{\tilde{t}_R} \mp \sqrt{(M^2_{\tilde{t}_L} - M^2_{\tilde{t}_R})^2 + 4m_t^2|X_t|^2}\right)$$

$\Rightarrow$ independent of ϕ_{X_t}

but $\theta_{\tilde{t}}$ is now complex

$SU(2)$ relation $\Rightarrow M_{\tilde{t}_L} = M_{\tilde{b}_L}$ $\Rightarrow$ relation between $m_{\tilde{t}_1}, m_{\tilde{t}_2}, \theta_{\tilde{t}}, m_{\tilde{b}_1}, m_{\tilde{b}_2}, \theta_{\tilde{b}}$

More on complex phases: Neutralinos and charginos:

Higgsinos and electroweak gauginos mix

charged:

$$\tilde{W}^+, \tilde{h}_u^+ \to \tilde{\chi}_1^+, \tilde{\chi}_2^+, \qquad \tilde{W}^-, \tilde{h}_d^- \to \tilde{\chi}_1^-, \tilde{\chi}_2^-$$

$\Rightarrow$ charginos: mass eigenstates

mass matrix given in terms of M_2, μ, $\tan\beta$

neutral:

$$\underbrace{\tilde{\gamma}, \tilde{Z},}_{\tilde{W}^0, \tilde{B}^0} \tilde{h}_u^0, \tilde{h}_d^0 \to \tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$$

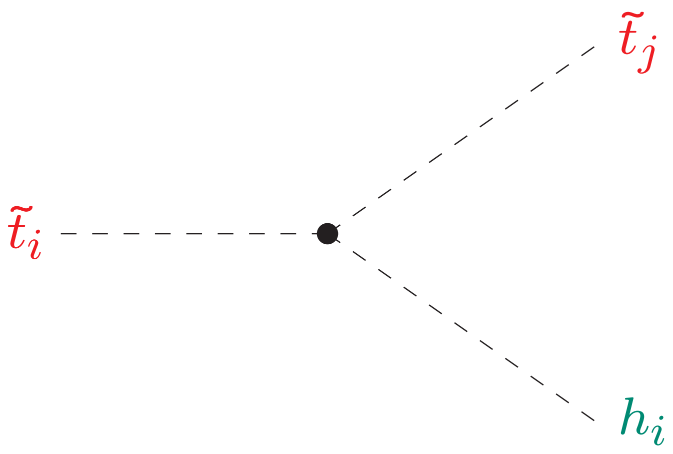
$\Rightarrow$ neutralinos: mass eigenstates

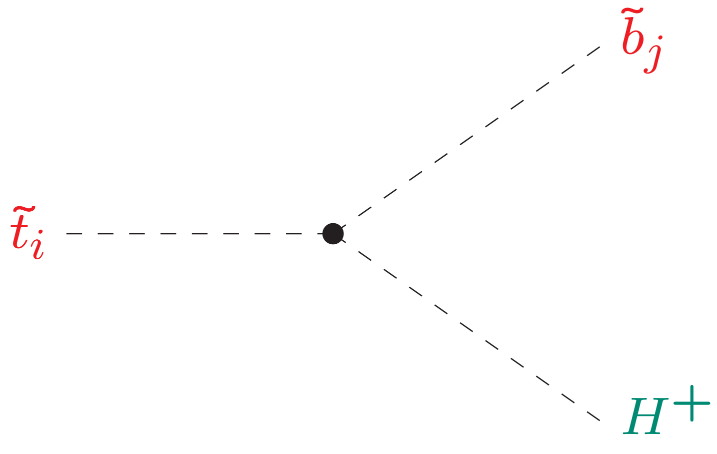
mass matrix given in terms of M_1, M_2, μ, $\tan\beta$

$\Rightarrow$ only one new parameter

$\Rightarrow$ MSSM predicts mass relations between neutralinos and charginos

Examples for processes with (external) stops and Higgs bosons:





- important decay modes of stops
- A_t and A_b directly enter the vertex
- possible source of Higgs bosons at the LHC/ILC
- ...

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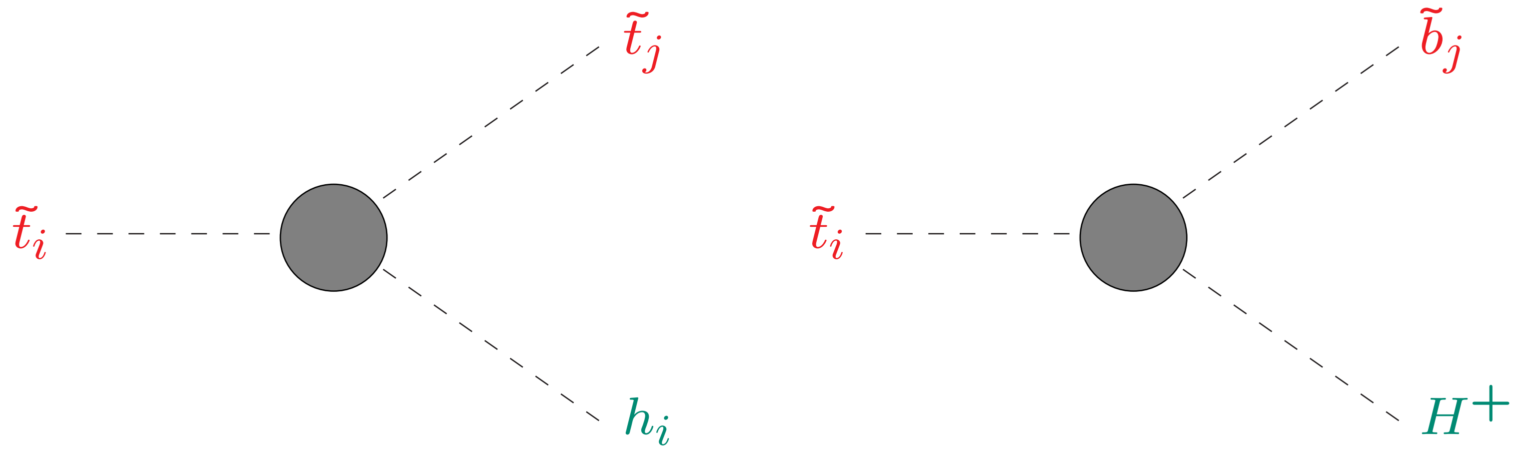

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⇒ higher-order corrections important!

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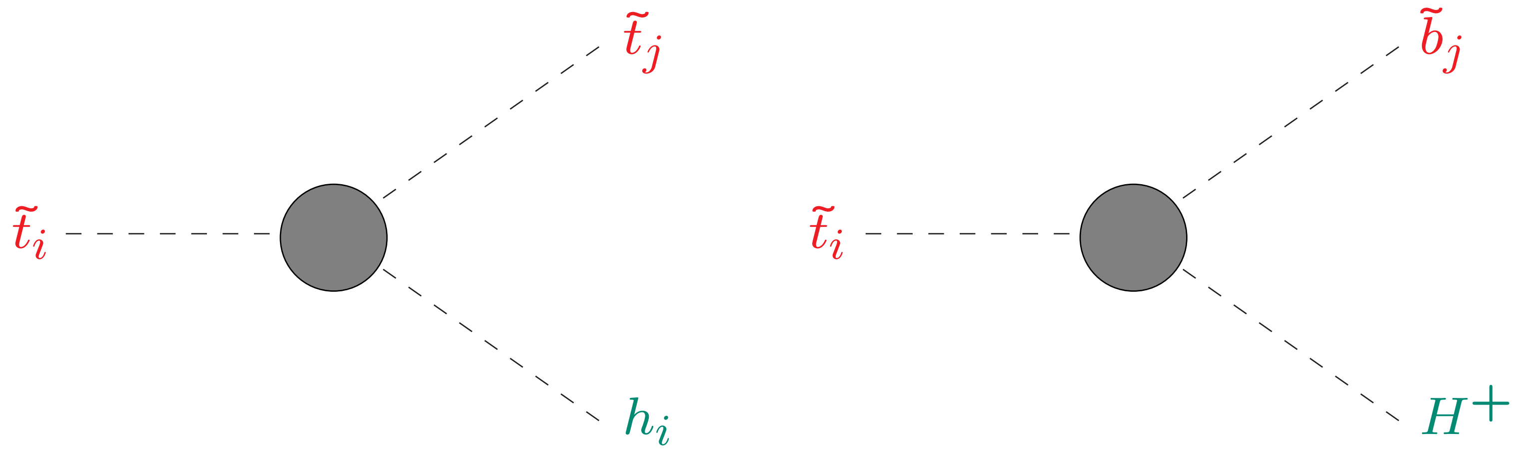

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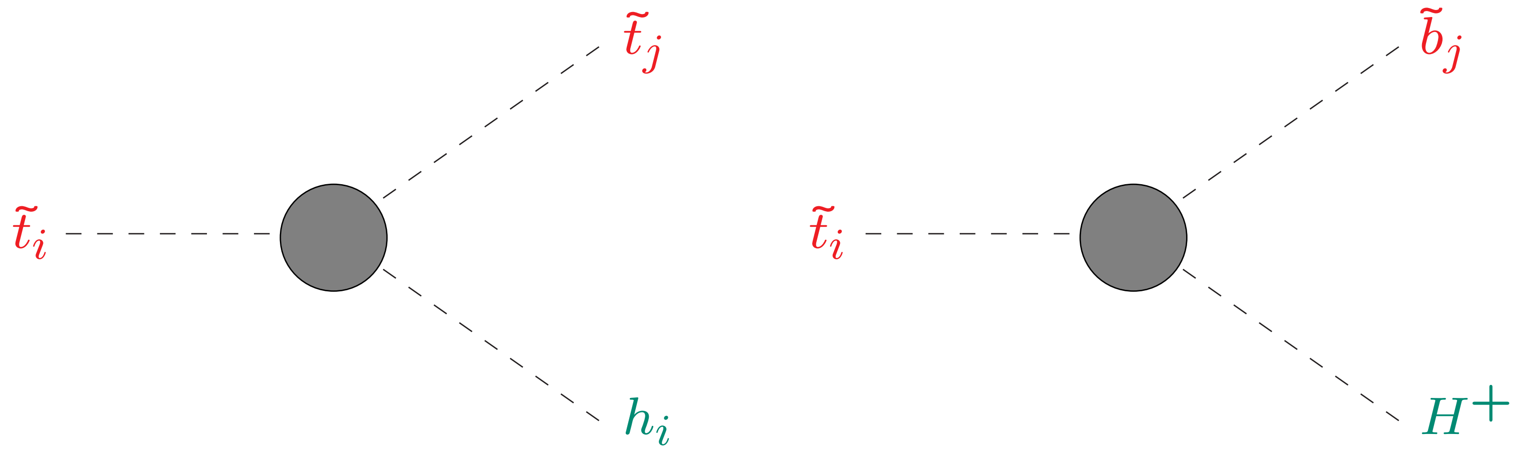

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⇒ simultaneous renormalization of stop and sbottom sector required!
⇒ with on-shell properties for external particles!

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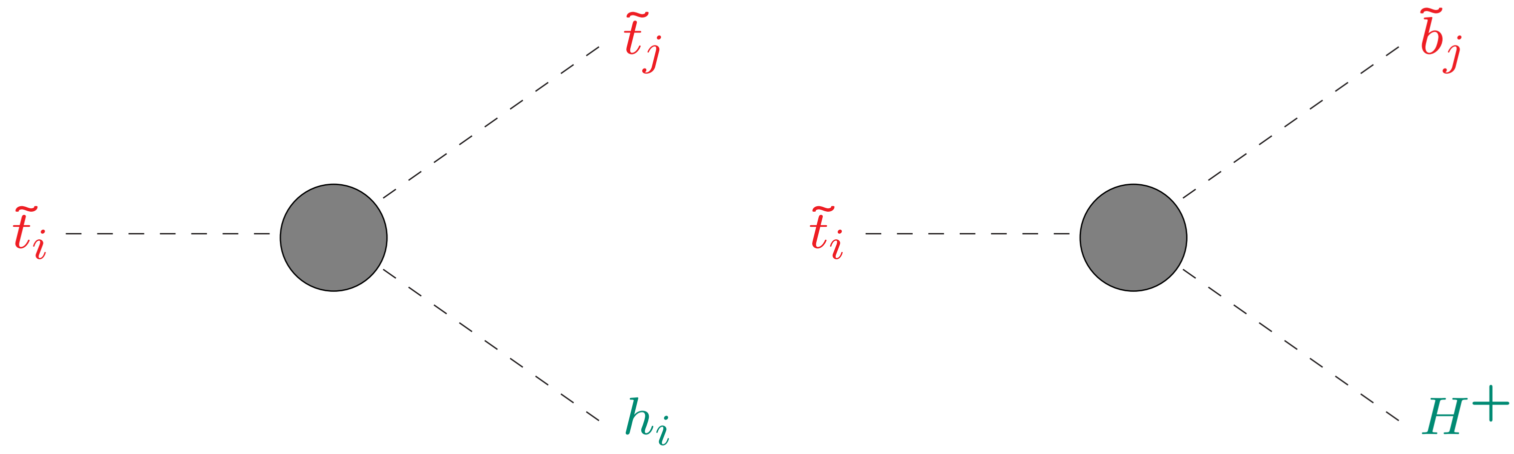
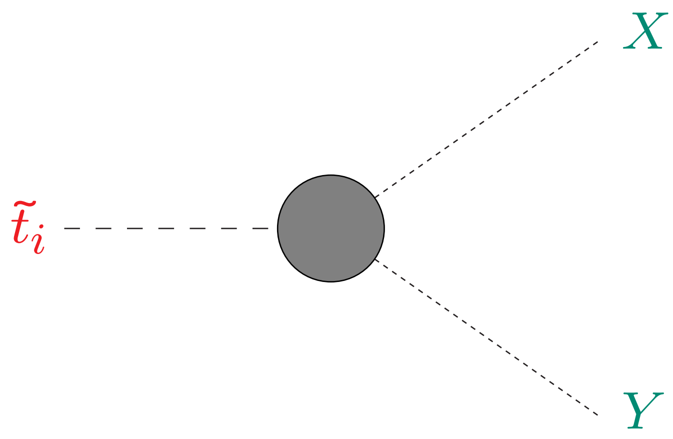


– important decay modes of stops
– A_t and A_b directly enter the vertex incl. complex phases!
– possible source of Higgs bosons at the LHC/ILC
– . . .

⇒ higher-order corrections important!

⇒ simultaneous renormalization of stop and sbottom sector required!
⇒ including complex phases!

The bigger picture: stop decays in the cMSSM



⇒ to get BRs right ⇒ all decays needed

⇒ (nearly) all sectors of the cMSSM enter as external particles

⇒ (nearly) all sectors of the cMSSM have to be renormalized simultaneously

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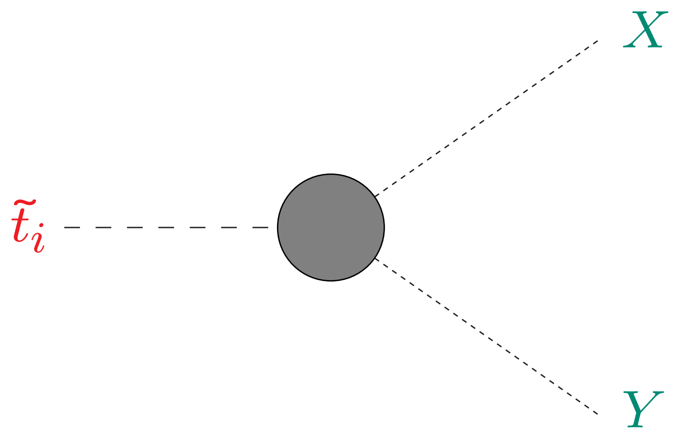

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Some LC relevant results later:

– (non-hadronic) chargino decays
– (non-hadronic) neutralino decays
– (heavy) stop decays
– (heavy) stau decays

LC potential:

The clean environment of the ILC would permit a detailed study of the SUSY decays

The ILC environment would result in an accuracy of the relative branching ratio

$$\mathrm{BR}^{\mathrm{full}} \equiv \frac{\Gamma^{\mathrm{full\ 1L}}(\mathrm{SUSY} \to \mathrm{xy})}{\Gamma^{\mathrm{full\ 1L}}_{\mathrm{tot}}}$$

$$\frac{\delta \mathrm{BR}}{\mathrm{BR}} \equiv \frac{\mathrm{BR}^{\mathrm{full}} - \mathrm{BR}^{\mathrm{tree}}}{\mathrm{BR}^{\mathrm{full}}}$$

close to the statistical uncertainty

$\Rightarrow$ Precision at the per-cent level possible!

$\Rightarrow$ theory precision at the per-cent level required!

Renormalization schemes in the stop/sbottom sector

("analogously" in the slepton sector!)

Generic parameter and field renormalization for scalar quarks:

$$\mathbf{D}_{\tilde{q}} = \mathbf{U}_{\tilde{q}} \mathbf{M}_{\tilde{q}} \mathbf{U}_{\tilde{q}}^{\dagger} \quad (\tilde{q} = \tilde{t}, \tilde{b})$$

$$\mathbf{U}_{\tilde{q}} \mathbf{M}_{\tilde{q}} \mathbf{U}_{\tilde{q}}^{\dagger} \to \mathbf{U}_{\tilde{q}} \mathbf{M}_{\tilde{q}} \mathbf{U}_{\tilde{q}}^{\dagger} + \mathbf{U}_{\tilde{q}} \delta\mathbf{M}_{\tilde{q}} \mathbf{U}_{\tilde{q}}^{\dagger} = \begin{pmatrix} m_{\tilde{q}_1}^2 & Y_q \\ Y_q^* & m_{\tilde{q}_2}^2 \end{pmatrix} + \begin{pmatrix} \delta m_{\tilde{q}_1}^2 & \delta Y_q \\ \delta Y_q^* & \delta m_{\tilde{q}_2}^2 \end{pmatrix}$$

$$\delta\mathbf{M}_{\tilde{q}_{12}} = U_{\tilde{q}_{11}}^* U_{\tilde{q}_{12}} (\delta m_{\tilde{q}_1}^2 - \delta m_{\tilde{q}_2}^2) + U_{\tilde{q}_{11}}^* U_{\tilde{q}_{22}} \delta Y_q + U_{\tilde{q}_{12}} U_{\tilde{q}_{21}}^* \delta Y_q^*$$

$$\begin{pmatrix} \tilde{q}_1 \\ \tilde{q}_2 \end{pmatrix} \to \left(\mathbb{1} + \frac{1}{2} \delta\mathbf{Z}_{\tilde{q}} \right) \begin{pmatrix} \tilde{q}_1 \\ \tilde{q}_2 \end{pmatrix} \quad \text{with} \quad \delta\mathbf{Z}_{\tilde{q}} = \begin{pmatrix} \delta Z_{\tilde{q}_{11}} & \delta Z_{\tilde{q}_{12}} \\ \delta Z_{\tilde{q}_{21}} & \delta Z_{\tilde{q}_{22}} \end{pmatrix}$$

Renormalization of the $t/\tilde{t}$ sector

$\to$ employ the widely used on-shell renormalization

$$\delta m_t = \frac{1}{2}\widetilde{\mathrm{Re}}\left\{m_t\left[\Sigma_t^L(m_t^2) + \Sigma_t^R(m_t^2)\right] + \left[\Sigma_t^{SL}(m_t^2) + \Sigma_t^{SR}(m_t^2)\right]\right\}$$

$$\delta m_{\tilde{t}_i}^2 = \widetilde{\mathrm{Re}}\Sigma_{\tilde{t}_{ii}}(m_{\tilde{t}_i}^2) \qquad (i = 1, 2)$$

$$\delta Y_t = \frac{1}{2}\widetilde{\mathrm{Re}}\left\{\Sigma_{\tilde{t}_{12}}(m_{\tilde{t}_1}^2) + \Sigma_{\tilde{t}_{12}}(m_{\tilde{t}_2}^2)\right\}$$

[W. Hollik, H. Rzehak '03]

This defines the counter term for A_t:

$$\delta A_t = \frac{1}{m_t}\Big[U_{\tilde{t}_{11}}U^*_{\tilde{t}_{12}}(\delta m^2_{\tilde{t}_1} - \delta m^2_{\tilde{t}_2}) + U_{\tilde{t}_{11}}U^*_{\tilde{t}_{22}}\delta Y_t^* + U^*_{\tilde{t}_{12}}U_{\tilde{t}_{21}}\delta Y_t - (A_t - \mu^* \cot\beta)\,\delta m_t\Big] + (\delta\mu^* \cot\beta - \mu^* \cot^2\beta\,\delta\tan\beta)$$

(with $\delta\mu$ from chargino/neutralino sector, $\delta\tan\beta$ from Higgs sector)

Field renormalization for on-shell squarks ($\tilde{t}$, $\tilde{b}$, ...):

Diagonal Z factors:

the real part of the residua of propagators is set to unity:

$$\widetilde{\mathrm{Re}} \frac{\partial \hat{\Sigma}_{\tilde{q}_{ii}}(k^2)}{\partial k^2}\Big|_{k^2=m^2_{\tilde{q}_i}} = 0 \qquad (i = 1, 2)$$

yielding

$$\mathrm{Re}\,\delta Z_{\tilde{q}_{ii}} = -\widetilde{\mathrm{Re}} \frac{\partial \Sigma_{\tilde{q}_{ii}}(k^2)}{\partial k^2}\Big|_{k^2=m^2_{\tilde{q}_i}} \qquad \mathrm{Im}\,\delta Z_{\tilde{q}_{ii}} = 0 \qquad (i = 1, 2)$$

Off-diagonal Z factors:

no transition from one squark to the other occurs:

$$\widetilde{\mathrm{Re}} \hat{\Sigma}_{\tilde{q}_{12}}(m^2_{\tilde{q}_1}) = 0 \qquad \widetilde{\mathrm{Re}} \hat{\Sigma}_{\tilde{q}_{12}}(m^2_{\tilde{q}_2}) = 0$$

yielding

$$\delta Z_{\tilde{q}_{12}} = +2 \frac{\widetilde{\mathrm{Re}} \Sigma_{\tilde{q}_{12}}(m^2_{\tilde{q}_2}) - \delta Y_q}{(m^2_{\tilde{q}_1} - m^2_{\tilde{q}_2})} \qquad \delta Z_{\tilde{q}_{21}} = -2 \frac{\widetilde{\mathrm{Re}} \Sigma_{\tilde{q}_{21}}(m^2_{\tilde{q}_1}) - \delta Y_q^*}{(m^2_{\tilde{q}_1} - m^2_{\tilde{q}_2})}$$

$SU(2)$ relation $\Rightarrow M_{\tilde{t}_L} = M_{\tilde{b}_L}$

"LL" soft SUSY-breaking term for $\tilde{q} = \{\tilde{t}, \tilde{b}\}$:

$$M^2_{\tilde{Q}_L}(\tilde{q}) = |U_{\tilde{q}11}|^2 m^2_{\tilde{q}_1} + |U_{\tilde{q}12}|^2 m^2_{\tilde{q}_2} - M_Z^2 c_{2\beta}(T_q^3 - Q_q s_W^2) - m_q^2$$

Keeping $SU(2)$ relation at the one-loop level leads to a shift in the soft SUSY-breaking parameters

[*A. Bartl, H. Eberl, K. Hidaka, S. Kraml, W. Majerotto, W. Porod, Y. Yamada '97, '98*]

[*A. Djouadi, P. Gambino, S.H., W. Hollik, C. Jünger, G. Weiglein '98*]

$$M^2_{\tilde{Q}_L}(\tilde{b}) = M^2_{\tilde{Q}_L}(\tilde{t}) + \delta M^2_{\tilde{Q}_L}(\tilde{t}) - \delta M^2_{\tilde{Q}_L}(\tilde{b})$$

with

$$\delta M^2_{\tilde{Q}_L}(\tilde{q}) = |U_{\tilde{q}11}|^2 \delta m^2_{\tilde{q}_1} + |U_{\tilde{q}12}|^2 \delta m^2_{\tilde{q}_2} - U_{\tilde{q}22} U^*_{\tilde{q}12} \delta Y_q - U_{\tilde{q}12} U^*_{\tilde{q}22} \delta Y_q^* - 2 m_q \delta m_q$$
$$+ M_Z^2\, c_{2\beta}\, Q_q\, \delta s_W^2 - (T_q^3 - Q_q s_W^2)(c_{2\beta}\, \delta M_Z^2 + M_Z^2\, \delta c_{2\beta})$$

$\to$ under control

Renormalizations of the $b/\tilde{b}$ sector in the complex MSSM:

scheme	$m_{\tilde{b}_{1,2}}$	m_b	A_b	Y_b	name
analogous to the $t/\tilde{t}$ sector: "OS"	OS	OS	—	OS	RS1
"m_b, A_b $\overline{\text{DR}}$"	OS	$\overline{\text{DR}}$	$\overline{\text{DR}}$	—	RS2
"m_b, Y_b $\overline{\text{DR}}$"	OS	$\overline{\text{DR}}$	—	$\overline{\text{DR}}$	RS3
"m_b $\overline{\text{DR}}$, Y_b OS"	OS	$\overline{\text{DR}}$	—	OS	RS4
"A_b $\overline{\text{DR}}$, ReY_b OS"	OS	—	$\overline{\text{DR}}$	ReY_b: OS	RS5
"A_b vertex, ReY_b OS"	OS	—	vertex	ReY_b: OS	RS6

"— " = dependent parameter

$\Rightarrow$ often very involved analytical dependences

$\rightarrow$ more combinations possible

. . . also tested

. . . upcoming results remain unchanged

Renormalization of the sbottom masses:

OS renormalization:

$$\delta m^2_{\tilde{b}_i} = \widetilde{\text{Re}}\Sigma_{\tilde{b}_{ii}}(m^2_{\tilde{b}_i}) \qquad (i = 1, 2)$$

Renormalization of the bottom mass:

OS renormalization:

$$\delta m_b = \frac{1}{2}\widetilde{\text{Re}}\left\{m_b\left[\Sigma_b^L(m_b^2) + \Sigma_b^R(m_b^2)\right] + \left[\Sigma_b^{SL}(m_b^2) + \Sigma_b^{SL}(m_b^2)\right]\right\}$$

$\overline{\text{DR}}$ renormalization:

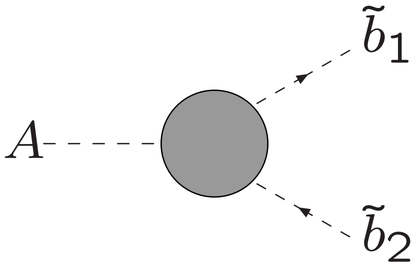
$$\delta m_b = \frac{1}{2}\widetilde{\text{Re}}\left\{m_b\left[\Sigma_b^L(m_b^2) + \Sigma_b^R(m_b^2)\right]_{\text{div}} + \left[\Sigma_b^{SL}(m_b^2) + \Sigma_b^{SL}(m_b^2)\right]_{\text{div}}\right\}$$

Renormalization of A_b:

DR renormalization: analogous to A_t:

$$\delta A_b = \frac{1}{m_b}\Big[U_{\tilde{b}_{11}} U^*_{\tilde{b}_{12}} \left(\widetilde{\text{Re}}\Sigma_{\tilde{b}_{11}}(m^2_{\tilde{b}_1})|_{\text{div}} - \widetilde{\text{Re}}\Sigma_{\tilde{b}_{22}}(m^2_{\tilde{b}_2})|_{\text{div}} \right)$$
$$+ \frac{1}{2} U^*_{\tilde{b}_{12}} U_{\tilde{b}_{21}} \left(\widetilde{\text{Re}}\Sigma_{\tilde{b}_{12}}(m^2_{\tilde{b}_1})|_{\text{div}} + \widetilde{\text{Re}}\Sigma_{\tilde{b}_{12}}(m^2_{\tilde{b}_2})|_{\text{div}} \right)$$
$$+ \frac{1}{2} U_{\tilde{b}_{11}} U^*_{\tilde{b}_{22}} \left(\widetilde{\text{Re}}\Sigma_{\tilde{b}_{12}}(m^2_{\tilde{b}_1})|_{\text{div}} + \widetilde{\text{Re}}\Sigma_{\tilde{b}_{12}}(m^2_{\tilde{b}_2})|_{\text{div}} \right)^*$$
$$- \frac{1}{2}(A_b - \mu^* \tan\beta)\, \widetilde{\text{Re}}\Big\{ m_b \left[\Sigma^L_b(m^2_b) + \Sigma^R_b(m^2_b) \right]_{\text{div}}$$
$$+ \left[\Sigma^{SL}_b(m^2_b) + \Sigma^{SR}_b(m^2_b) \right]_{\text{div}} \Big\} \Big] + \delta\mu^*|_{\text{div}} \tan\beta + \mu^*\, \delta\tan\beta$$

Vertex renormalization:



$$\hat{=} \quad i\,\hat{\Lambda}(p^2_A, p^2_{\tilde{b}_1}, p^2_{\tilde{b}_2})$$

$$\text{via} \quad \widetilde{\text{Re}}\hat{\Lambda}(0, m^2_{\tilde{b}_1}, m^2_{\tilde{b}_1}) + \widetilde{\text{Re}}\hat{\Lambda}(0, m^2_{\tilde{b}_2}, m^2_{\tilde{b}_2}) \stackrel{!}{=} 0$$

Renormalization of Y_b:

OS renormalization:

$$\delta Y_b = \frac{1}{2}\widetilde{\text{Re}}\left\{\Sigma_{\tilde{b}_{12}}(m^2_{\tilde{b}_1}) + \Sigma_{\tilde{b}_{12}}(m^2_{\tilde{b}_2})\right\}$$

$\overline{\text{DR}}$ renormalization:

$$\delta Y_b = \frac{1}{2}\widetilde{\text{Re}}\left\{\Sigma_{\tilde{b}_{12}}(m^2_{\tilde{b}_1})|_{\text{div}} + \Sigma_{\tilde{b}_{12}}(m^2_{\tilde{b}_2})|_{\text{div}}\right\}$$

ReY_b OS renormalization

$$\text{Re}\delta Y_b = \frac{1}{2}\text{Re}\left\{\widetilde{\text{Re}}\Sigma_{\tilde{b}_{12}}(m^2_{\tilde{b}_1}) + \widetilde{\text{Re}}\Sigma_{\tilde{b}_{12}}(m^2_{\tilde{b}_2})\right\}$$

Existing analyses all in the real MSSM:

- [A. Bartl et al. '98] [L. Jin, C. Li '01]
  "OS" used for stop and sbottom decays
  ($\to$ implemented into SDecay)

- [C. Weber, K. Kovarik, H. Eberl, W. Majerotto '07]
  similar to "m_b, A_b $\overline{\text{DR}}$" used for Higgs decays to sfermions

- [A. Arhrib, R. Benbrik '04]
  an "OS" scheme used for $\tilde{f} \to \tilde{f}' V$

- [Q. Li, L. Jin, C. Li '02]
  an "OS" scheme with running m_t, m_b, A_t, A_b used for $\tilde{t}_2 \to \tilde{t}_1 \phi$

- [H. Eberl et al. '10]
  pure $\overline{\text{DR}}$ scheme used for stop decays

- [A. Brignole, G. Degrassi, P. Slavich and F. Zwirner '02]
  [S.H., W. Hollik, H. Rzehak, G. Weiglein '04]
  real "A_b vertex, ReY_b OS" used for two-loop Higgs self-energies

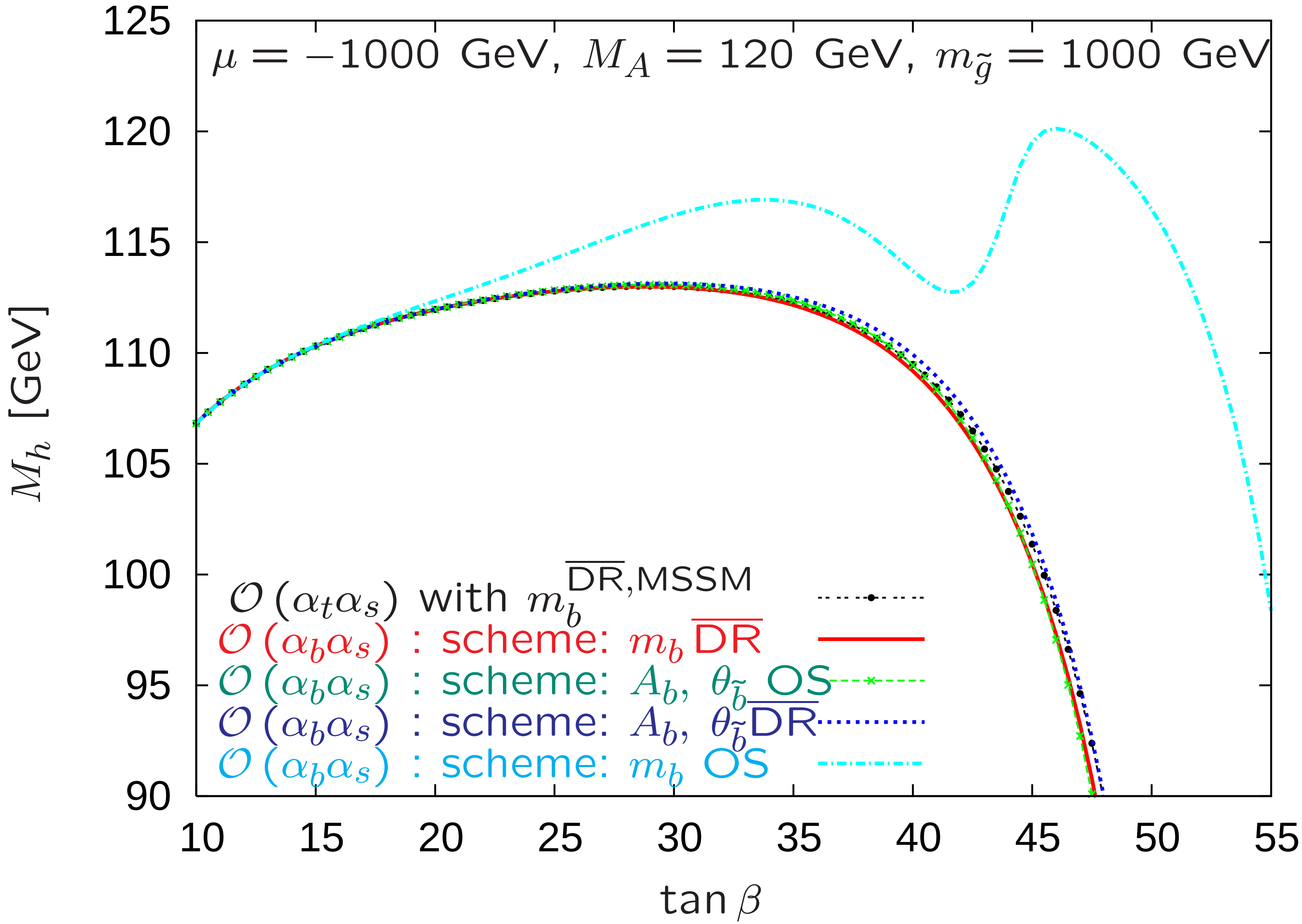
Analysis of the renormalization schemes

Numerical scenarios:

Scen.	$M_{H^\pm}$	$m_{\tilde{t}_2}$	μ	A_t	A_b	M_1	M_2	M_3
S1	150	600	200	900	400	200	300	800
S2	180	900	300	1800	1600	150	200	400

Scen.	$\tan\beta$	$m_{\tilde{t}_1}$	$m_{\tilde{t}_2}$	$m_{\tilde{b}_1}$	$m_{\tilde{b}_2}$
S1	2	293.391	600.000	441.987	447.168
	20	235.073	600.000	418.824	439.226
	50	230.662	600.000	400.815	449.638
S2	2	495.014	900.000	702.522	707.598
	20	445.885	900.000	678.531	695.180
	50	442.416	900.000	628.615	697.202

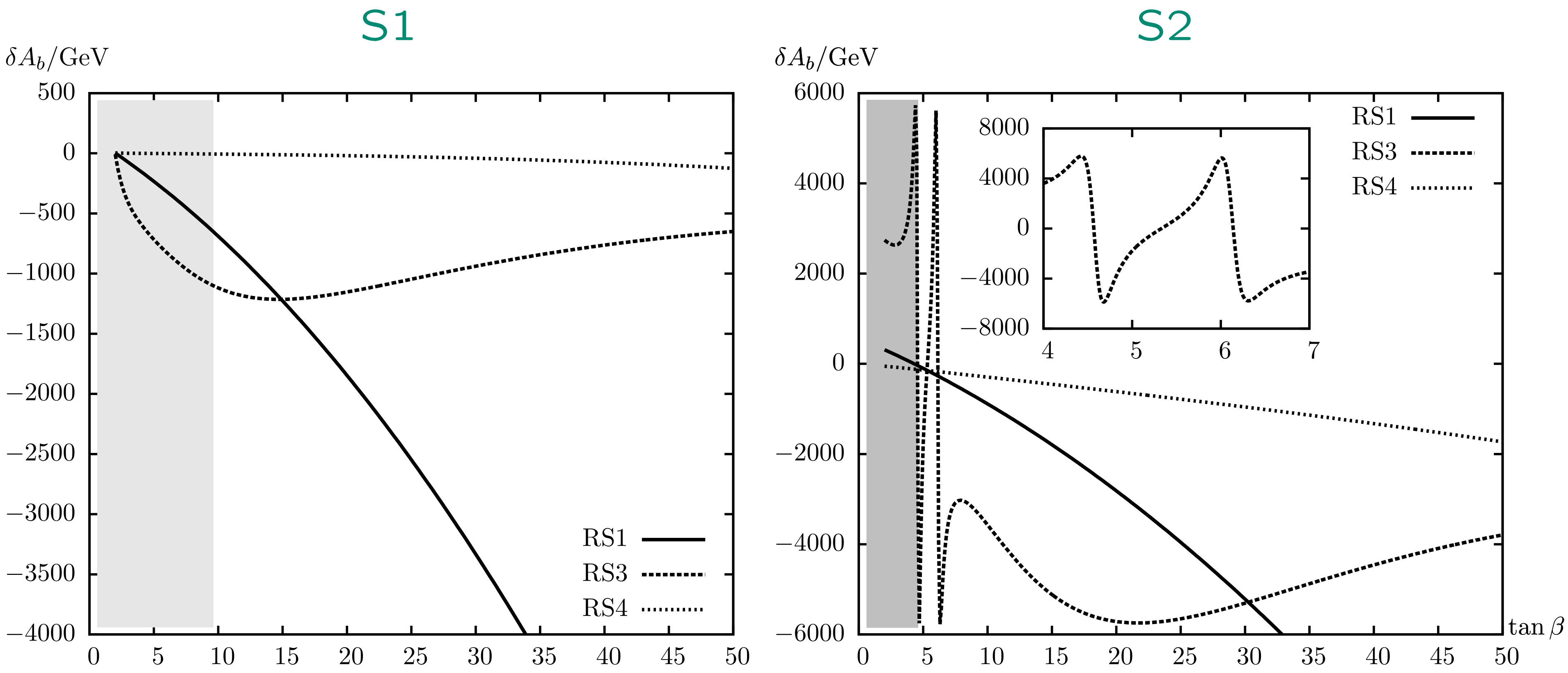
"OS" scheme: $\delta A_b = \frac{1}{m_b}\left[-(A_b - \mu^* \tan\beta)\,\delta m_b + \ldots\right]$



$\Rightarrow$ fails already for Higgs boson self-energies

Problems of non-A_b renormalizations:

$$\delta A_b|_{\text{fin}} = \frac{1}{m_b}\left[U_{\tilde{b}_{11}} U^*_{\tilde{b}_{12}} \left(\delta m^2_{\tilde{b}_1} - \delta m^2_{\tilde{b}_2}\right)\right]_{\text{fin}} + \dots$$

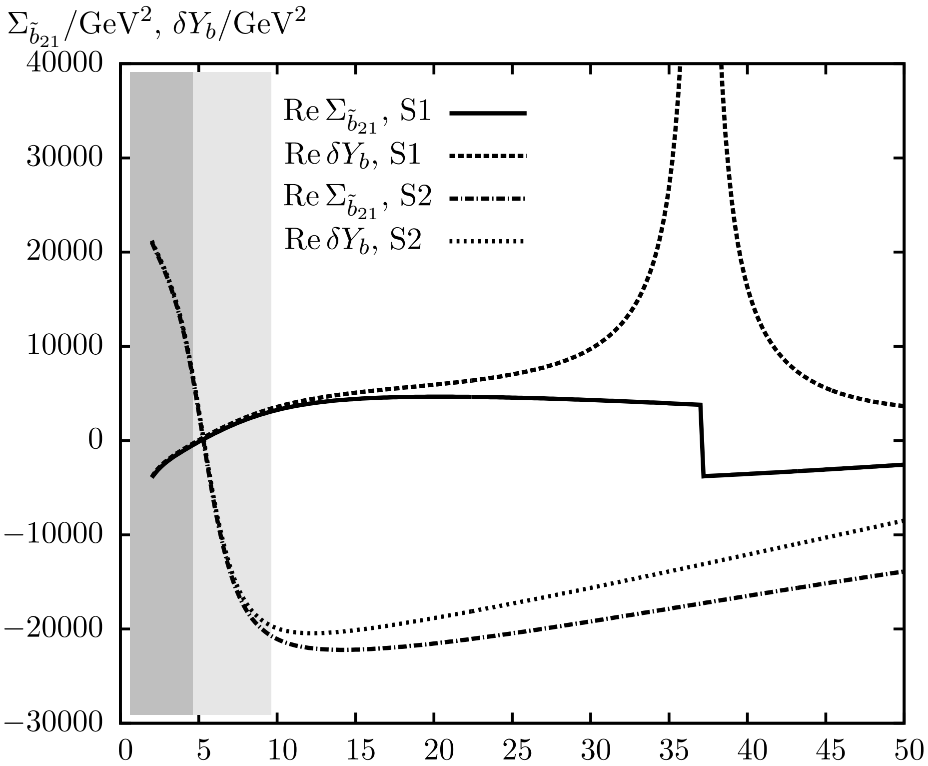


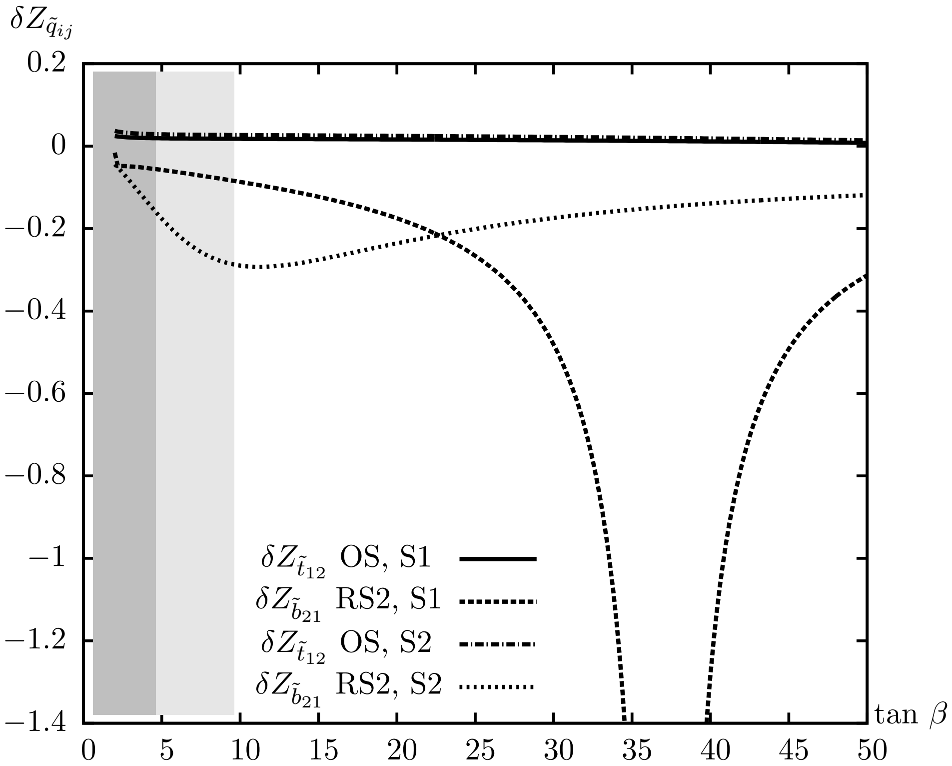
$\Rightarrow$ too large contributions to A_b are induced

Problems of m_b–A_b renormalizations:

$$\delta Y_b = \frac{U_{\tilde{b}_{11}} U_{\tilde{b}_{21}}}{|U_{\tilde{b}_{11}}|^2 - |U_{\tilde{b}_{12}}|^2} \left(\delta m^2_{\tilde{b}_1} - \delta m^2_{\tilde{b}_2} \right) + \ldots, \qquad \delta Z_{\tilde{b}_{21}} = -2 \, \frac{\mathrm{Re}\Sigma_{\tilde{b}_{21}}(m^2_{\tilde{b}_2}) - \delta Y_b}{m^2_{\tilde{b}_1} - m^2_{\tilde{b}_2}}$$

$\Rightarrow$ divergence for $|U_{\tilde{b}_{11}}| = |U_{\tilde{b}_{12}}|$ reached for $\tan\beta \approx 37$ in S1:





Problems of non-m_b renormalizations:

"A_b $\overline{\text{DR}}$, ReY_b OS" (RS5): (rMSSM)

$$\delta m_b = -\frac{m_b\, \delta A_b + \delta S}{(A_b - \mu \tan\beta)}$$

$\Rightarrow$ divergent for $A_b = \mu \tan\beta$

"A_b vertex, ReY_b OS" (RS6): (rMSSM)

$$\delta m_b = \frac{\delta S + F}{\mu\,(\tan\beta + 1/\tan\beta)}$$

$\Rightarrow$ no problem in the rMSSM!

"A_b vertex, ReY_b OS" (RS6): (cMSSM: $U_- = U_{\tilde{b}_{11}} U^*_{\tilde{b}_{22}} - U_{\tilde{b}_{12}} U^*_{\tilde{b}_{21}}$)

$$\frac{1}{\delta m_b} \sim 4\,\mu\, \tan^3\beta \left[\mathrm{Re} U_- \left(|U_{\tilde{b}_{11}}|^2 - |U_{\tilde{b}_{12}}|^2 \right) + \mathrm{Im}\, U_- \frac{4\, m_b}{m^2_{\tilde{b}_1} - m^2_{\tilde{b}_2}} \mathrm{Im} \left(U^*_{\tilde{b}_{11}} U_{\tilde{b}_{12}} A_b \right) \right]$$

$\Rightarrow$ divergences appear depending on ϕ_{A_b}!

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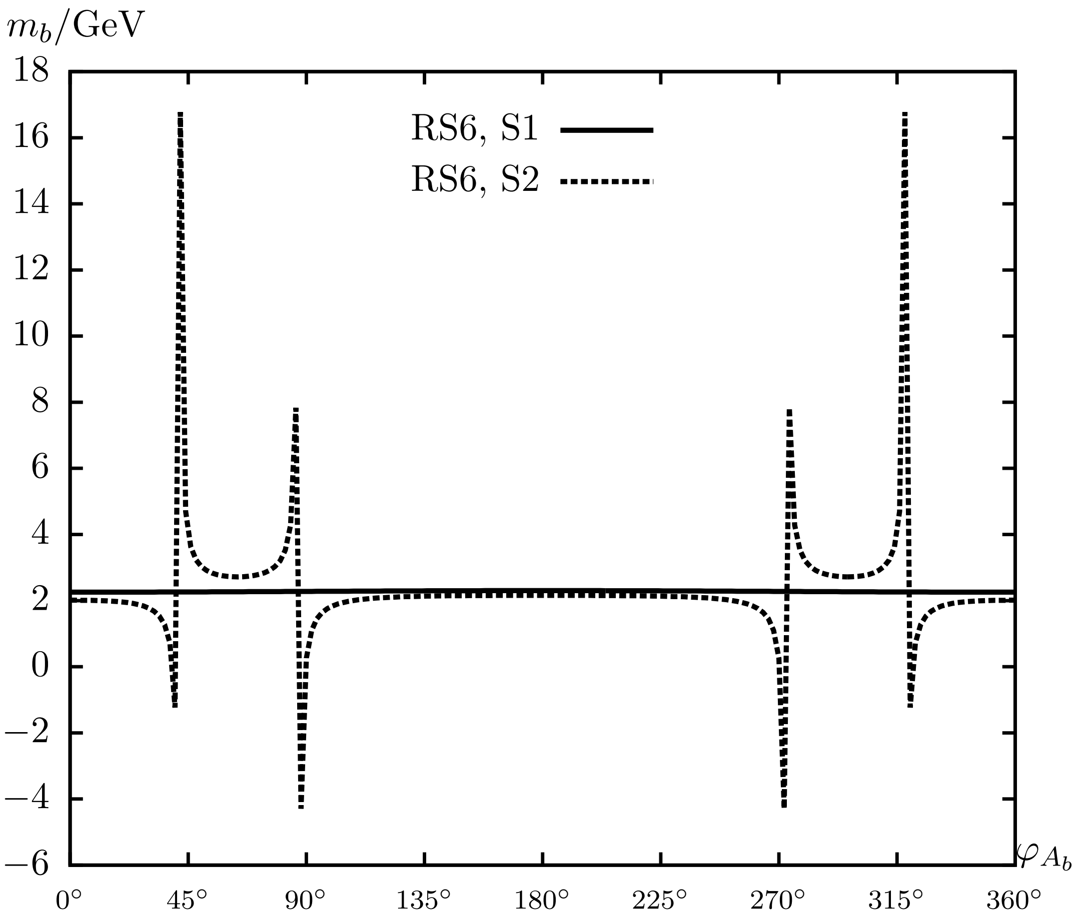

What is the "preferred" renormalization scheme?

one counterterm is a "dependent" quantity

$\Rightarrow$ no scheme can be identified that shows "good" behavior
over the full cMSSM parameter space

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Most "robust" behavior:

– RS2: "m_b, A_b $\overline{\text{DR}}$"
  ⇒ problems only for maximal sbottom mixing
– RS6: "A_b vertex, ReY_b OS"
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All problems could be avoided in a pure $\overline{\text{DR}}$ scheme
$\Rightarrow$ not suited for external stops and sbottoms

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⇒ we choose RS2: "m_b, A_b $\overline{\text{DR}}$" as our "preferred" scheme

Renormalization in the chargino/neutralino sector

$\Rightarrow$ Two "OS" schemes:

1. **Scheme I:**

   [*T. Fritzsche, S.H., H. Rzehak, C. Schappacher '11*][*S.H., F. v.d. Pahlen, C. Schappacher '12*]

$$\left(\left[\widetilde{\mathbf{Re}}\hat{\Sigma}_{\tilde{\chi}^-}(p)\right]_{ii}\tilde{\chi}_i^-(p)\right)\Big|_{p^2=m^2_{\tilde{\chi}_i^\pm}} = 0 \qquad (i=1,2)\ ,$$

$$\left(\left[\widetilde{\mathbf{Re}}\hat{\Sigma}_{\tilde{\chi}^0}(p)\right]_{11}\tilde{\chi}_1^0(p)\right)\Big|_{p^2=m^2_{\tilde{\chi}_1^0}} = 0$$

2. **Scheme II:**

   [*A. Fowler, G. Weiglein '09*]

$$\left(\left[\mathbf{Re}\hat{\Sigma}_{\tilde{\chi}^-}(p)\right]_{ii}\tilde{\chi}_i^-(p)\right)\Big|_{p^2=m^2_{\tilde{\chi}_i^\pm}} = 0 \qquad (i=1,2)\ ,$$

$$\left(\left[\mathbf{Re}\hat{\Sigma}_{\tilde{\chi}^0}(p)\right]_{11}\tilde{\chi}_1^0(p)\right)\Big|_{p^2=m^2_{\tilde{\chi}_1^0}} = 0$$

Some comments:

– Scheme I and Scheme II agree for real parameters

– Both schemes can easily be extended to other variants, e.g.

$$\text{CCN}_i \ (i = 1, 2, 3, 4) \quad \text{or} \quad \text{CNN}_{ijk} \ (i = 1, 2; j, k = 1, 2, 3, 4)$$

→ relevant for $|\mu| \approx M_2$ [*F. v.d. Pahlen et al., in progress*]
(see also: [*Drees et al. '11*])

– Both schemes require a shift of three (neutralino) masses to their on-shell value:

$$\Delta m_{\tilde{\chi}_i^0} = -\frac{1}{2}\text{Re}\Big\{ m_{\tilde{\chi}_i^0} \Big(\hat{\Sigma}^L_{\tilde{\chi}_i^0}(m^2_{\tilde{\chi}_i^0}) + \hat{\Sigma}^R_{\tilde{\chi}_i^0}(m^2_{\tilde{\chi}_i^0}) \Big) + \hat{\Sigma}^{SL}_{\tilde{\chi}_i^0}(m^2_{\tilde{\chi}_i^0}) + \hat{\Sigma}^{SR}_{\tilde{\chi}_i^0}(m^2_{\tilde{\chi}_i^0}) \Big\}$$

$$m^{\text{OS}}_{\tilde{\chi}_i^0} = m_{\tilde{\chi}_i^0} + \Delta m_{\tilde{\chi}_i^0}$$

Comparison of the renormalization schemes

Parameters:

$\tan\beta$	$M_{H^\pm}$	$m_{\tilde{\chi}_2^\pm}$	$m_{\tilde{\chi}_1^\pm}$	$M_{\tilde{l}_L}$	$M_{\tilde{l}_R}$	A_l	$M_{\tilde{q}_L}$	$M_{\tilde{q}_R}$	A_q
20	160	600	350	300	310	400	1300	1100	2000

$$|M_1| = \frac{5}{3}\tan^2\theta_W M_2 \approx \frac{1}{2}M_2$$

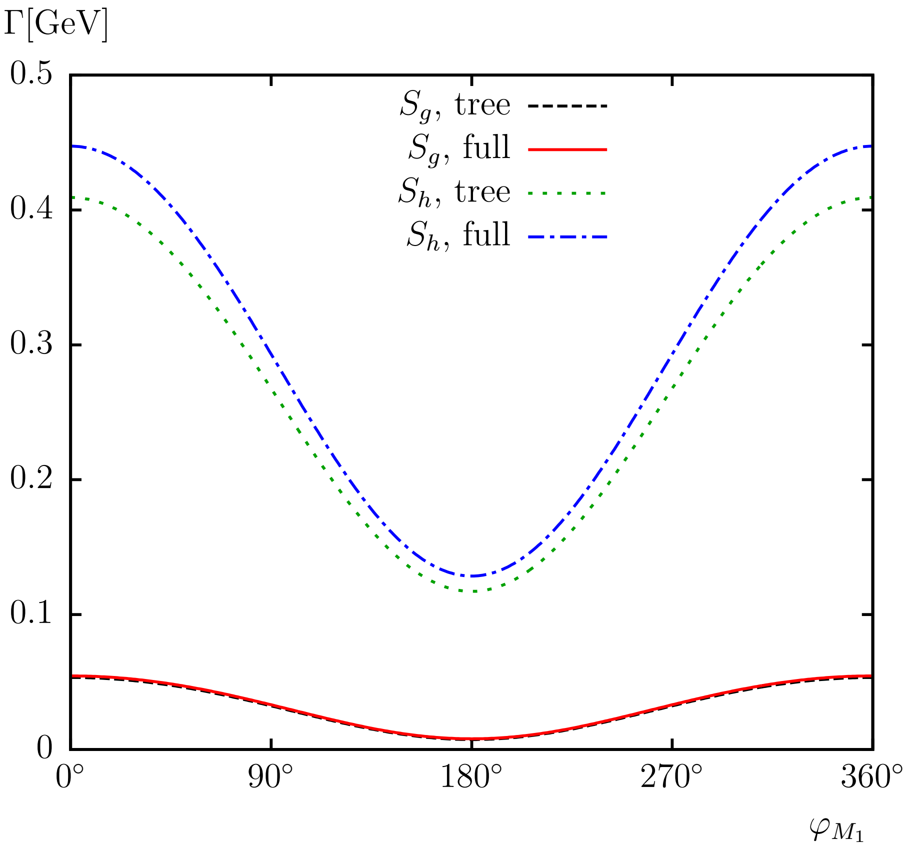
$\mathcal{S}_g : \mu > M_2$ ($\tilde{\chi}_4^0$ more higgsino-like)

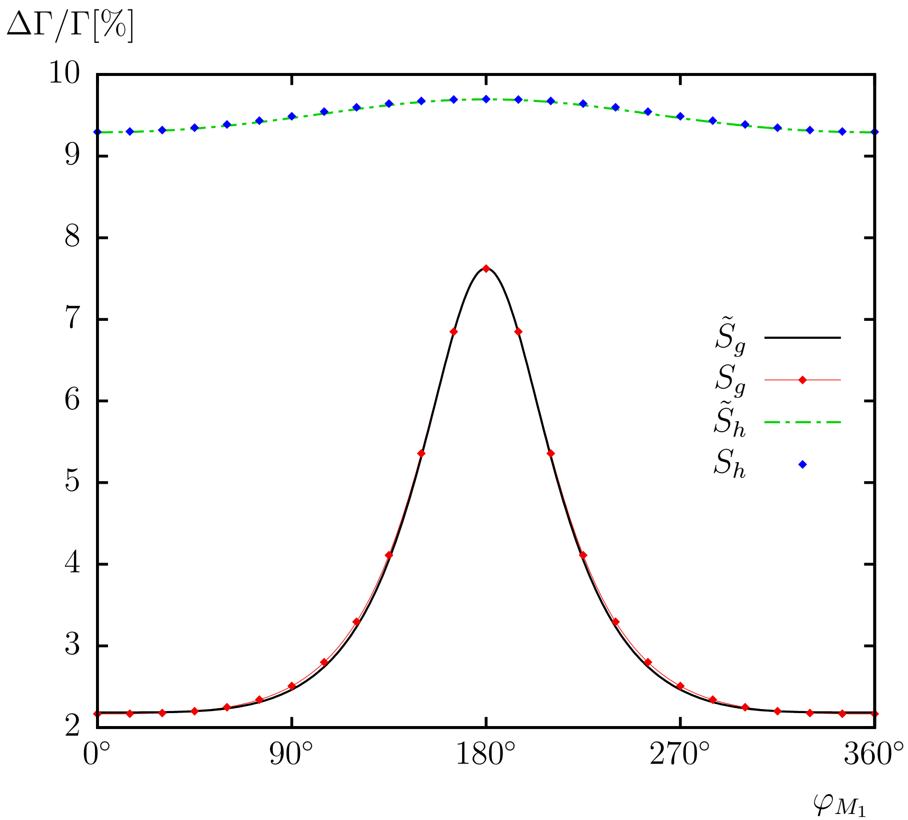
$\mathcal{S}_h : \mu < M_2$ ($\tilde{\chi}_4^0$ more gaugino-like)

Scen.	$m_{\tilde{\chi}_2^\pm}$	$m_{\tilde{\chi}_1^\pm}$	$m_{\tilde{\chi}_4^0}$	$m_{\tilde{\chi}_3^0}$	$m_{\tilde{\chi}_2^0}$	$m_{\tilde{\chi}_1^0}$	μ	M_2	M_1
$\mathcal{S}_g$	600.0	350.0	600.0	364.2	359.6	267.2	362.1	581.8	277.7
$\mathcal{S}_h$	600.0	350.0	600.1	586.2	349.9	171.4	581.8	362.1	172.8

$\Gamma(\tilde{\chi}^0_4 \to \tilde{\chi}^0_1 h_1)$: dependence on φ_{M_1}

[A. Bharucha, S.H., F. v.d. Pahlen, C. Schappacher '12]



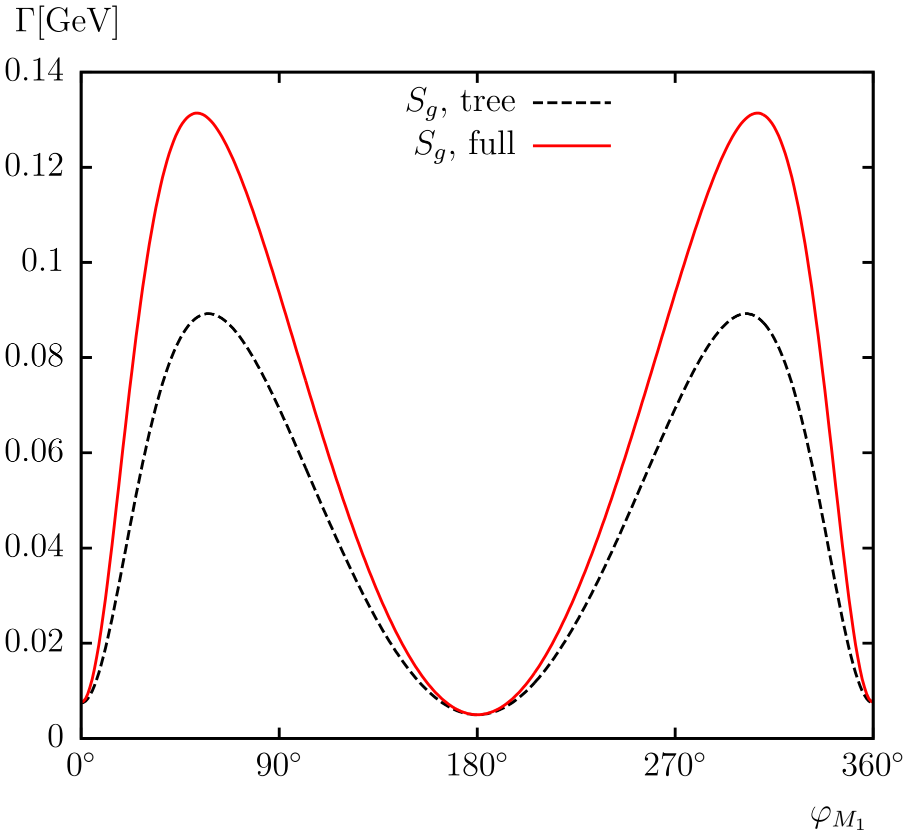


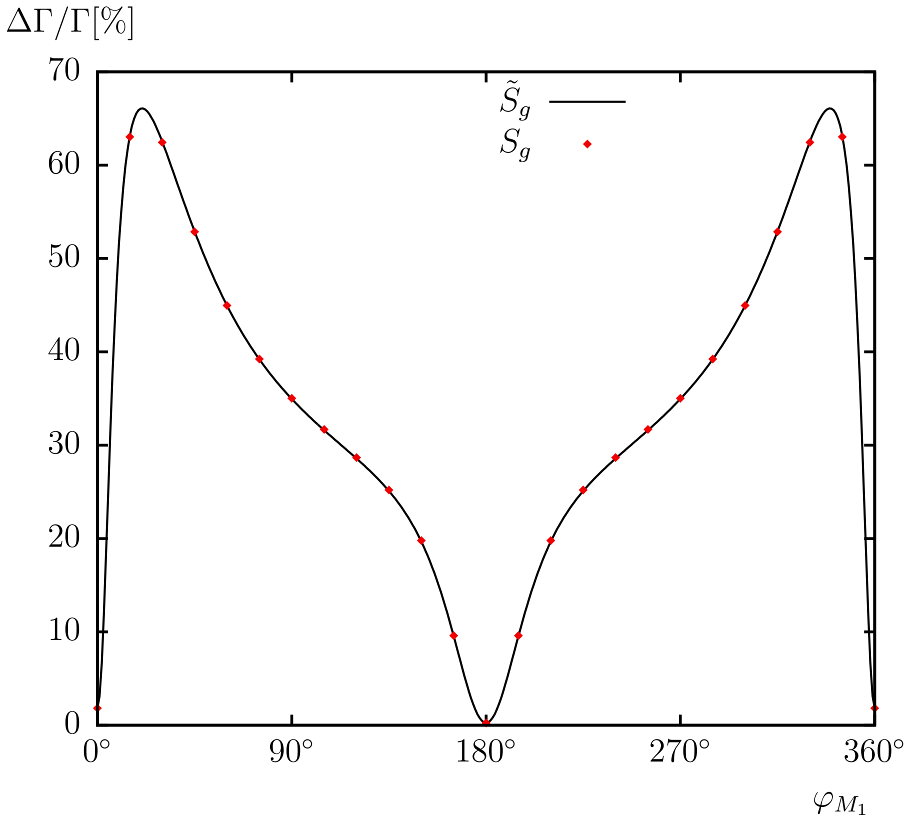
⇒ one-loop corrections under control and non-negligible

⇒ renormalization schemes agree (as expected)

$\Gamma(\tilde{\chi}_4^0 \to \tilde{\chi}_3^0 h_1)$: dependence on φ_{M_1}

[*A. Bharucha, S.H., F. v.d. Pahlen, C. Schappacher '12*]



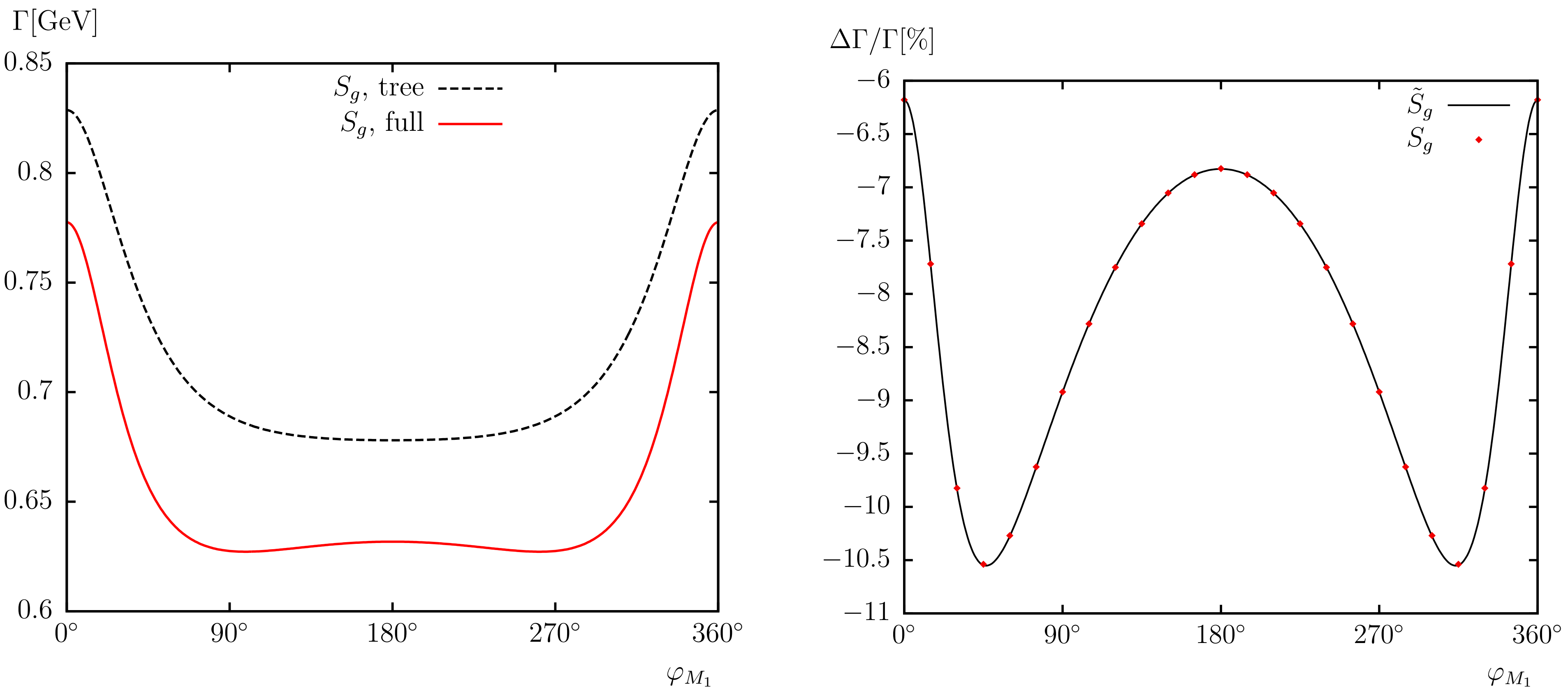


$\Rightarrow$ one-loop corrections under control and non-negligible

$\Rightarrow$ renormalization schemes agree (as expected)

$\Gamma(\tilde{\chi}^0_4 \to \tilde{\chi}^0_3 Z)$: dependence on φ_{M_1}

[A. Bharucha, S.H., F. v.d. Pahlen, C. Schappacher '12]



⇒ one-loop corrections under control and non-negligible

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Renormalization summary:

– LC precision requires all calculations at the per-cent level

– full complex MSSM renormalized

[*A. Bharucha, T. Fritzsche, T. Hahn, S.H., F.v.d. Pahlen, H. Rzehak, C. Schappacher '11 - '13*]

– stable and well behaved results over nearly complete parameter space

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$\Rightarrow$ **go and make your prediction!**

3. Results for the MSSM Higgs at the LC

A. Status and latest results for M_h prediction
$\Rightarrow$ see talk by S.H. Thursday 9am
(some brand new results! :-)
$\Rightarrow$ still far away from LC precision!

B. Effects for the charged Higgs boson mass

C. Status of $e^+e^- \to Zh$

D. Recent results for decays to Higgs bosons

3B) Effects for the charged Higgs boson mass

Experimental resolution:

$M_{H^\pm} = 200$ GeV:

$$\text{LHC}: \Rightarrow \delta M_{H^\pm} \approx 1.5 \text{ GeV}$$

$$\text{LC}: \Rightarrow \delta M_{H^\pm} \approx 0.5 \text{ GeV}$$

Higher masses:

$$\text{LHC}: \Rightarrow \delta M_{H^\pm} \approx 1 - 2\%$$

$$\text{LC}: ???$$

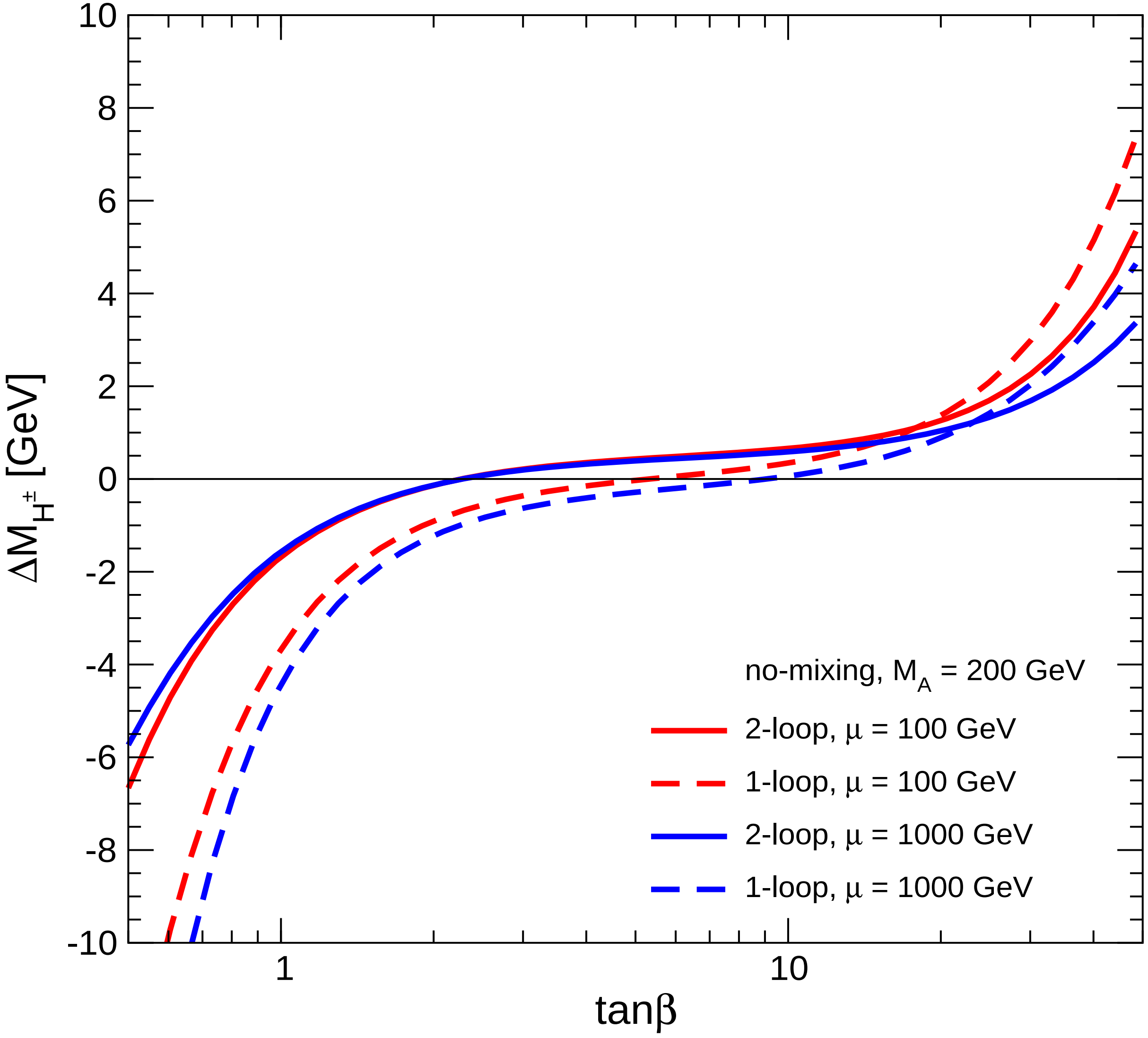
Numerical examples: [M. Frank, L. Galeta, T.Hahn, S.H., W. Hollik, H. Rzehak, G. Weiglein '13]

$\rightarrow$ no-mixing scenario, with variation of

– M_A : tree-level parameter
– $\tan\beta$: tree-level parameter
– μ : enters via Δ_b

($m_h^{\max}$ scenario similar, slightly smaller corrections)

2-loop, $\tan\beta$ varied:



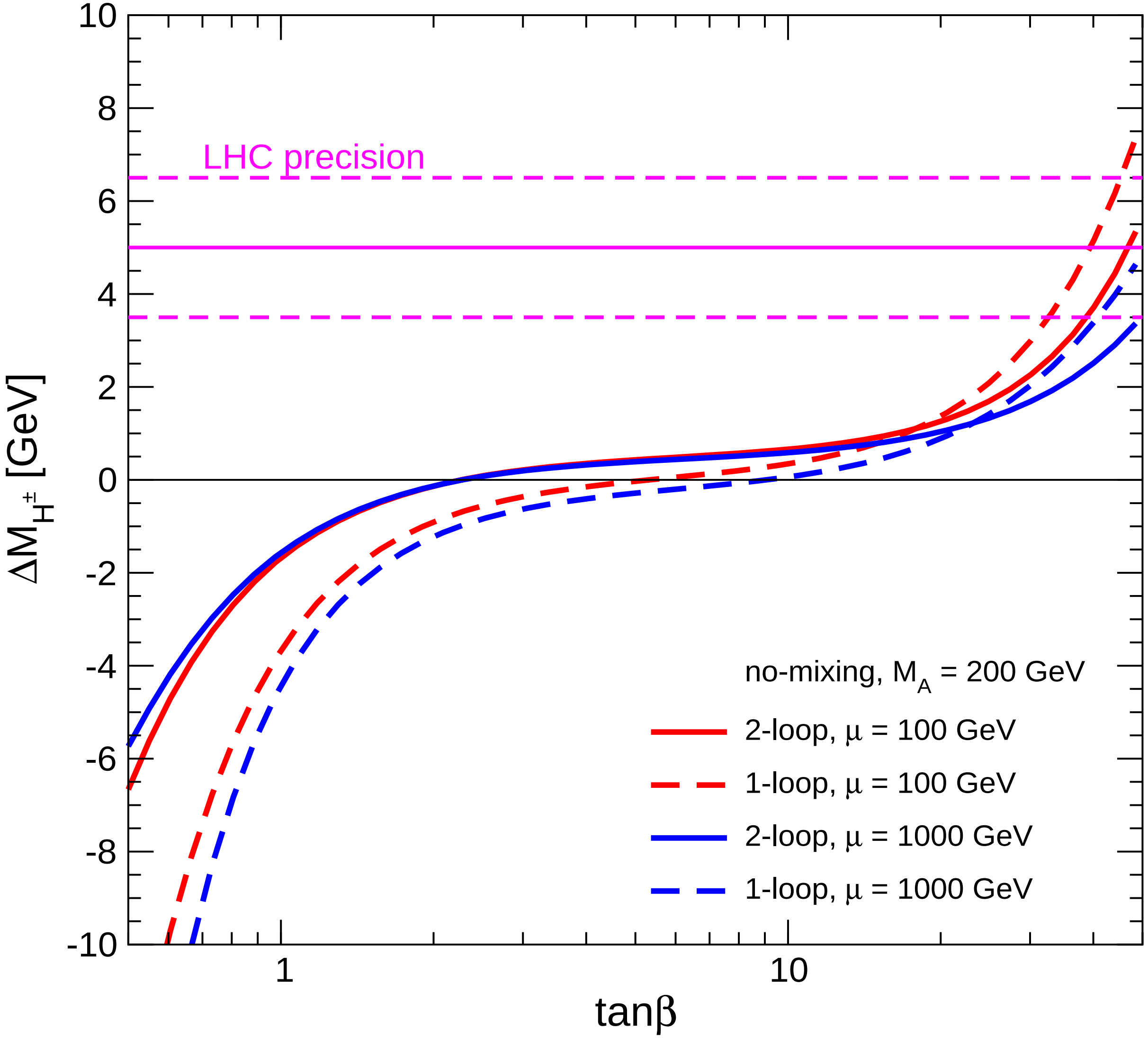
small $\tan\beta$:

$\Delta M_{H^\pm} \gtrsim 4$ GeV

large $\tan\beta$:

$\Delta M_{H^\pm} \sim 2$ GeV

2-loop, $\tan\beta$ varied:



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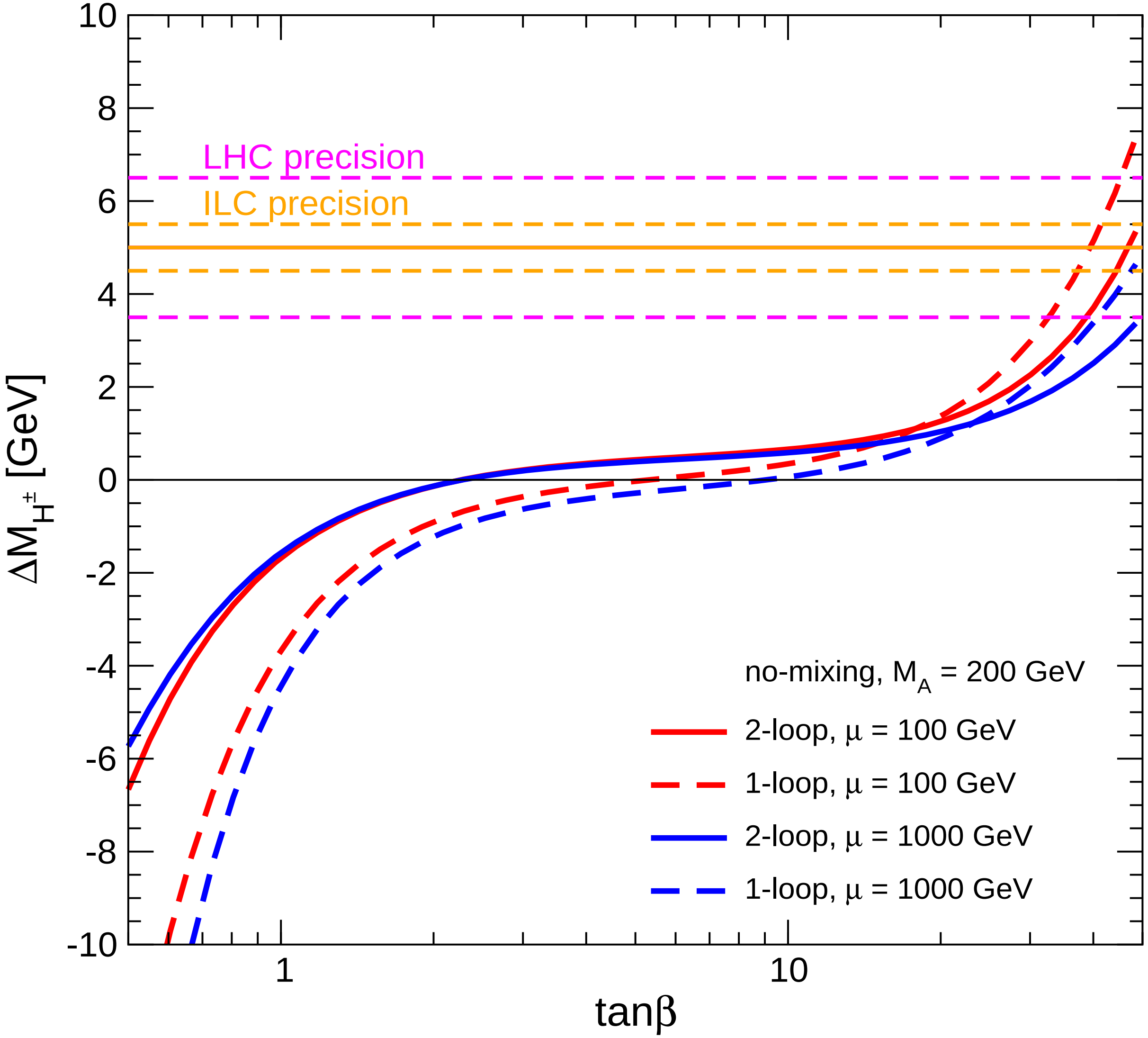

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$\Delta M_{H^\pm} \sim 2$ GeV

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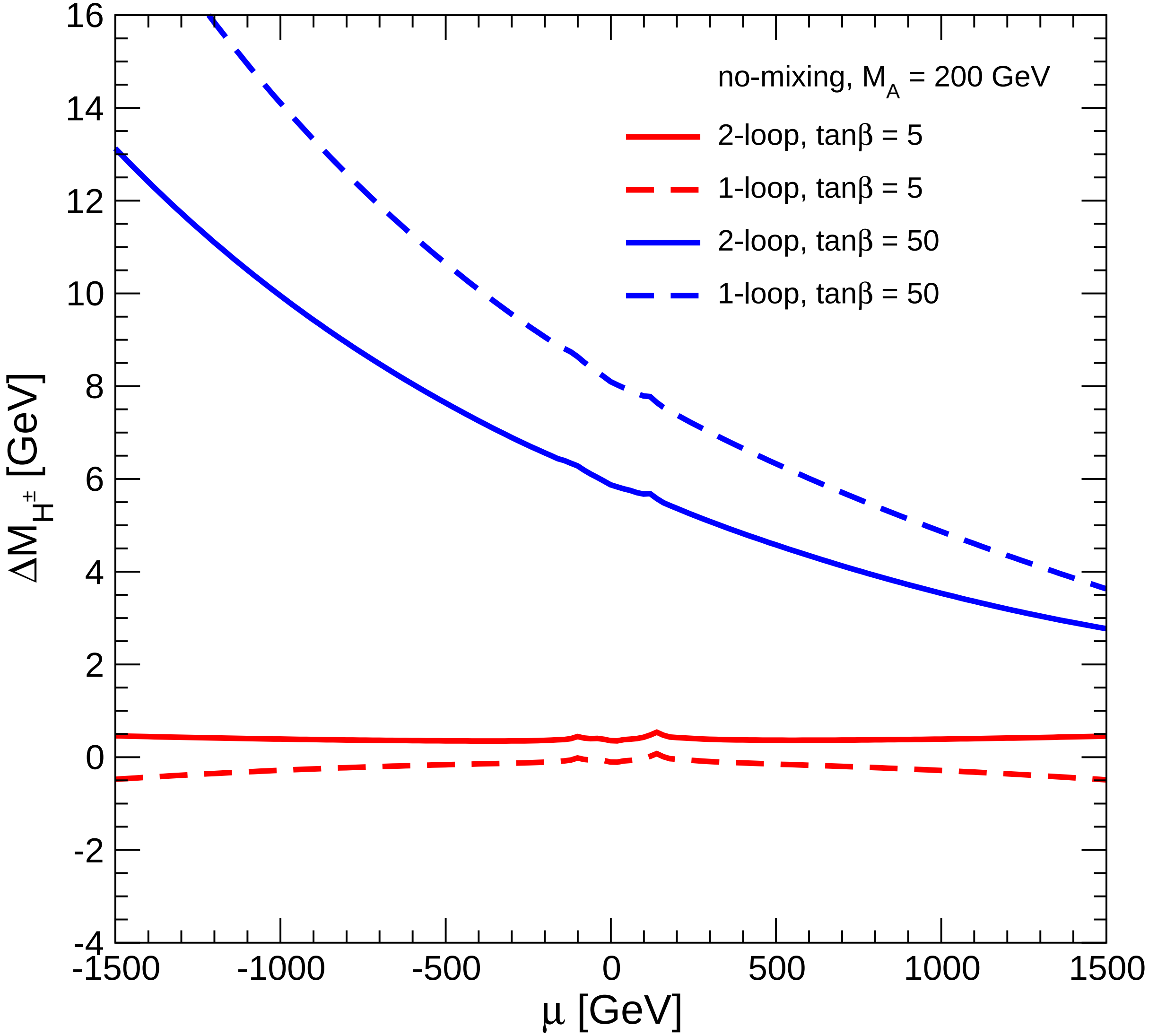


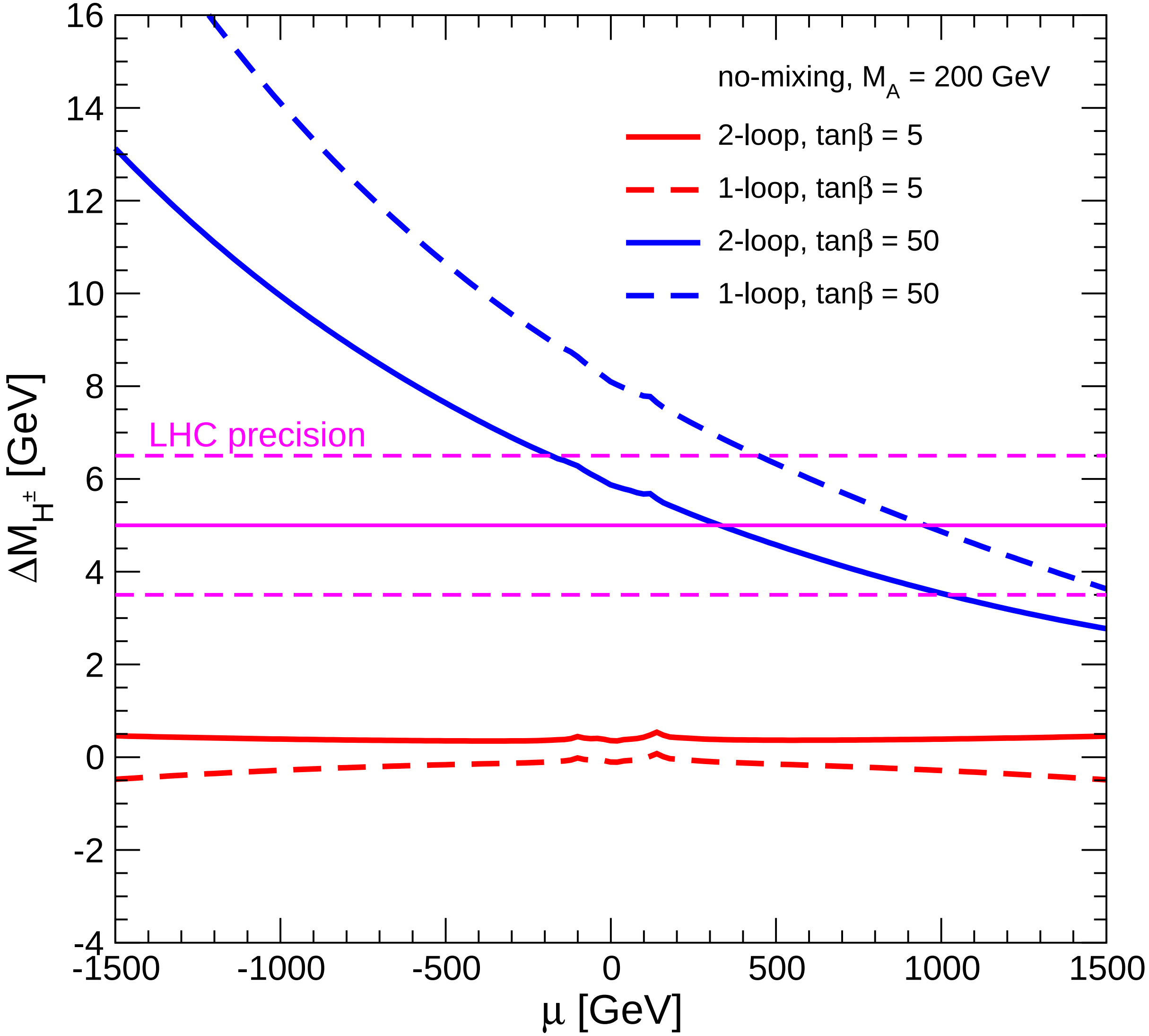
negative μ:

$\Delta M_{H^\pm} = 2 - 5$ GeV

positive μ:

$\Delta M_{H^\pm} = 0.5 - 2$ GeV

2-loop, μ varied:



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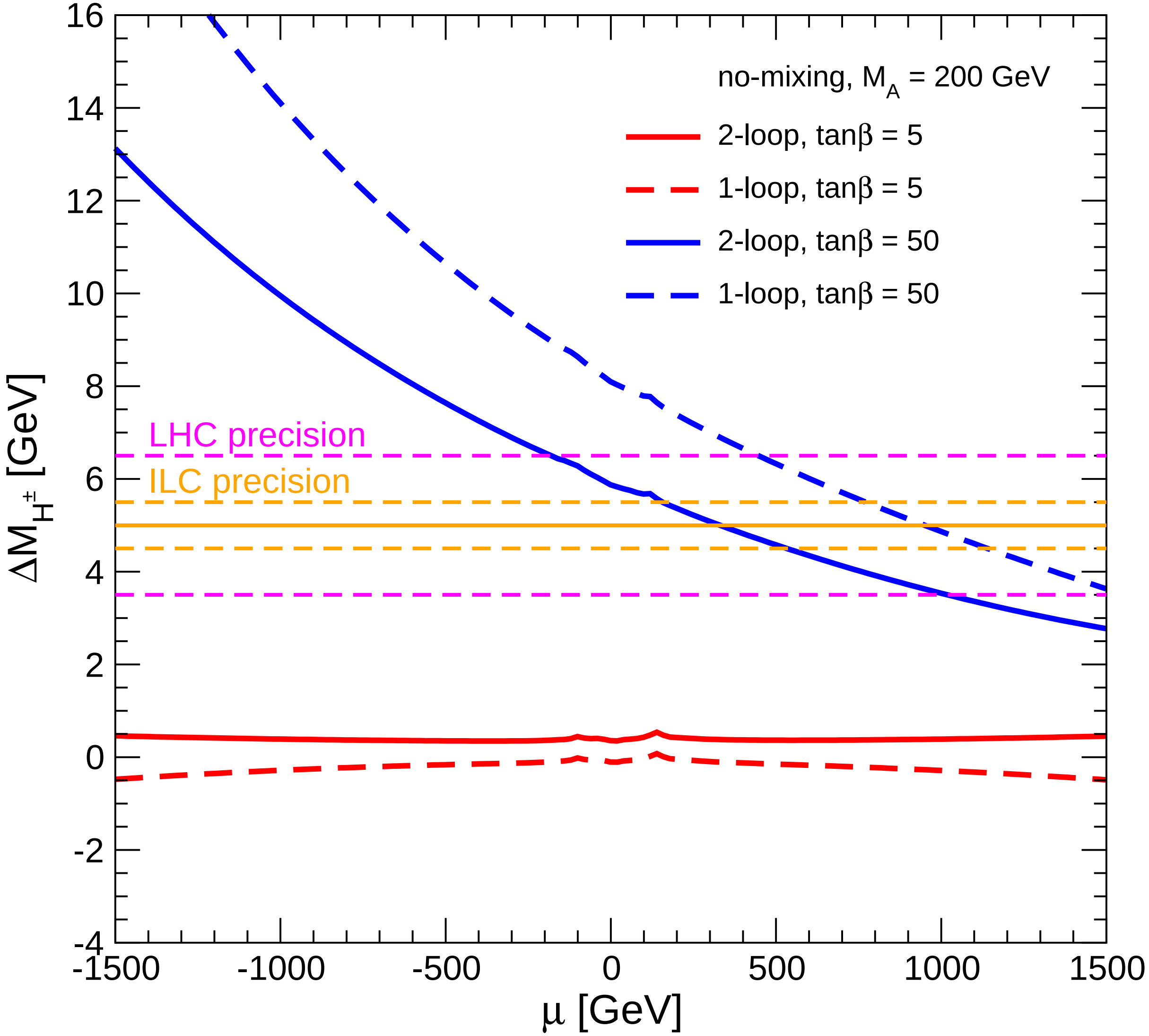

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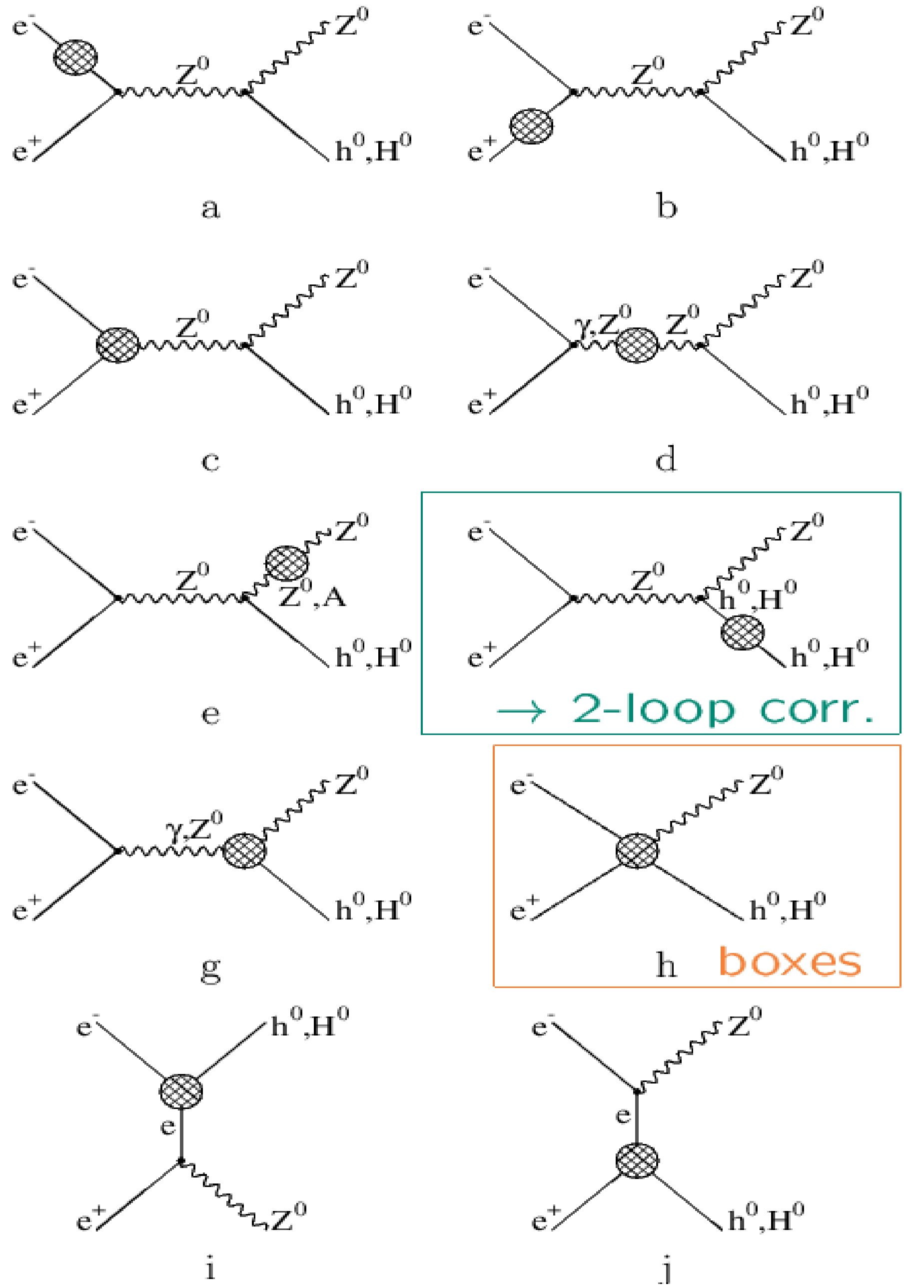
3C) Status of $e^+e^- \to Zh$

Only full one-loop calculation in the rMSSM:

[S.H., W. Hollik, J. Rosiek, G. Weiglein '01]

Feynman diagrams $\Rightarrow$



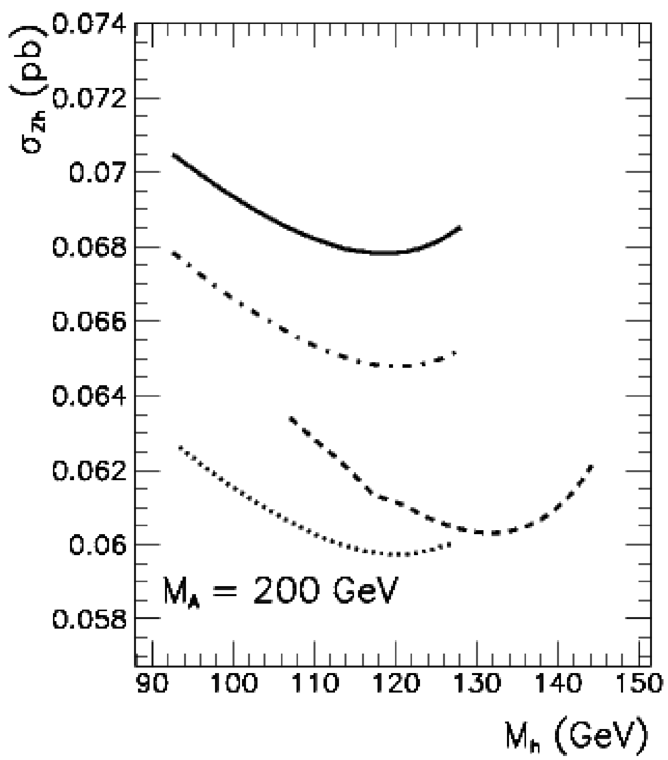
$e^+e^- \to hZ$, $\sqrt{s} = 500$ GeV, maximal $\tilde{t}$ mixing:

$M_{\tilde{q}} = 1$ TeV, $M_{\tilde{l}} = 300$ GeV, $M_2 = \mu = 200$ GeV

$M_A = 200$ GeV, $\tan\beta$ varied

solid: FD 2L (with box) , dot-dashed: FD 2L (no box)

dashed: FD 1L , dotted: $\alpha_{\rm eff}$ RG approximation



⇒ diagrammatic 2L result necessary to reach LC precision!   cMSSM??

3D) Chargino decays to Higgs bosons

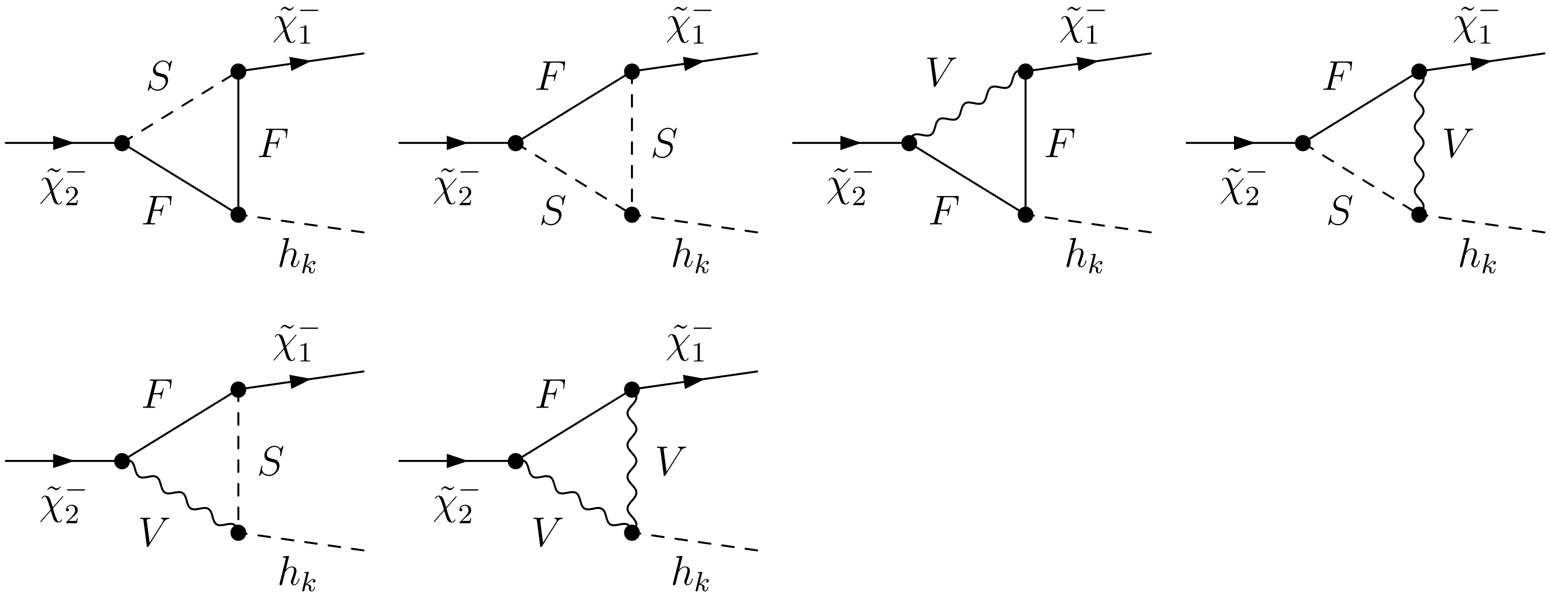
$$\Gamma(\tilde{\chi}_2^\pm \to \tilde{\chi}_1^\pm h_k) \qquad (k = 1,2,3) \;,$$
$$\Gamma(\tilde{\chi}_2^\pm \to \tilde{\chi}_1^\pm Z) \;,$$
$$\Gamma(\tilde{\chi}_i^\pm \to \tilde{\chi}_j^0 H^\pm) \qquad (i = 1,2,\; j = 1,2,3,4) \;,$$
$$\Gamma(\tilde{\chi}_i^\pm \to \tilde{\chi}_j^0 W^\pm) \qquad (i = 1,2,\; j = 1,2,3,4) \;,$$
$$\Gamma(\tilde{\chi}_i^\pm \to \tilde{l}_k^\pm \nu_l) \qquad (i = 1,2,\; l = e,\mu,\tau,\; k = 1,2) \;,$$
$$\Gamma(\tilde{\chi}_i^\pm \to \tilde{\nu}_l l^\pm) \qquad (i = 1,2,\; l = e,\mu,\tau) \;.$$

No hadronic decays yet . . .

Scen.	$\tan\beta$	$M_{H^\pm}$	$m_{\tilde{\chi}_2^\pm}$	$m_{\tilde{\chi}_1^\pm}$	$M_{\tilde{l}_L}$	$M_{\tilde{l}_R}$	A_l
$\mathcal{S}$	20	160	650	350	300	310	400

$$\mathcal{S}_> : \mu > M_2 \quad (\tilde{\chi}_2^\pm \text{ more higgsino-like})$$
$$\mathcal{S}_< : \mu < M_2 \quad (\tilde{\chi}_2^\pm \text{ more gaugino-like})$$

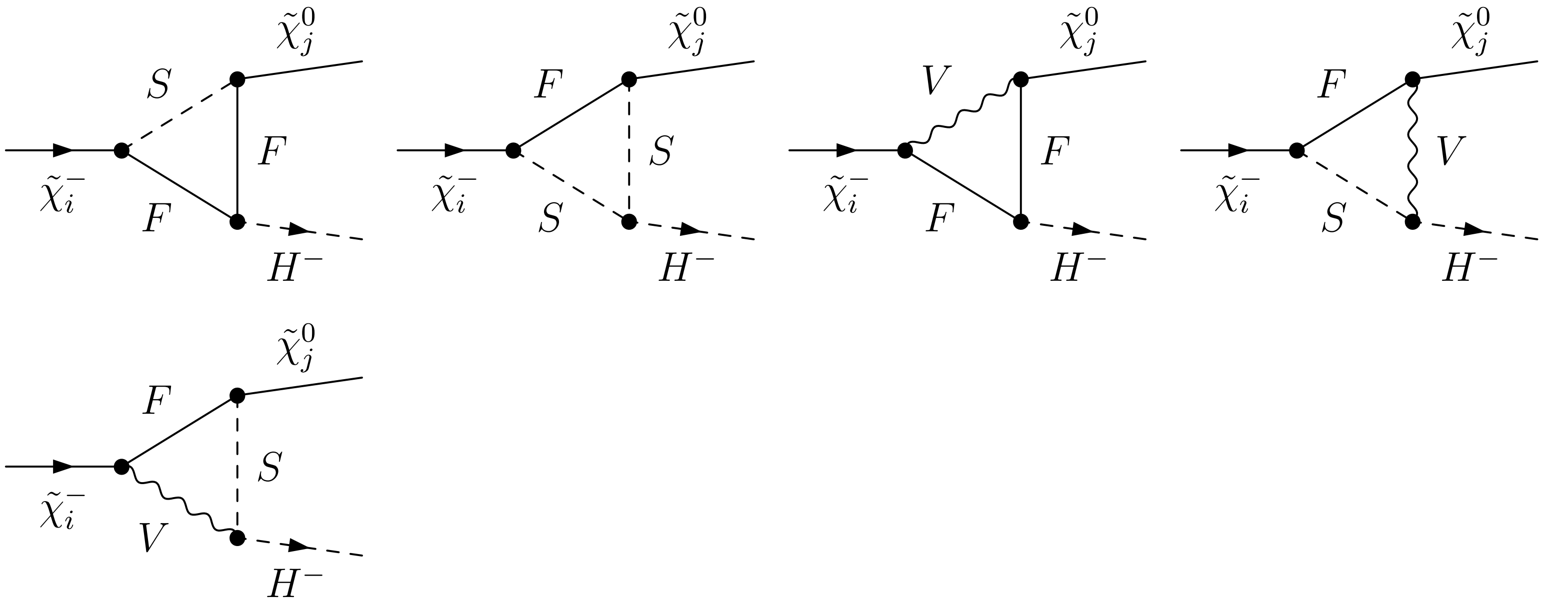
Feynman diagrams for $\tilde{\chi}_2^- \to \tilde{\chi}_1^- h_k$



– including Z–A or G–A transition contribution on the external Higgs boson leg

– including all soft/hard QED/QCD diagrams

Feynman diagrams for $\tilde{\chi}_i^- \to \tilde{\chi}_j^0 H^-$

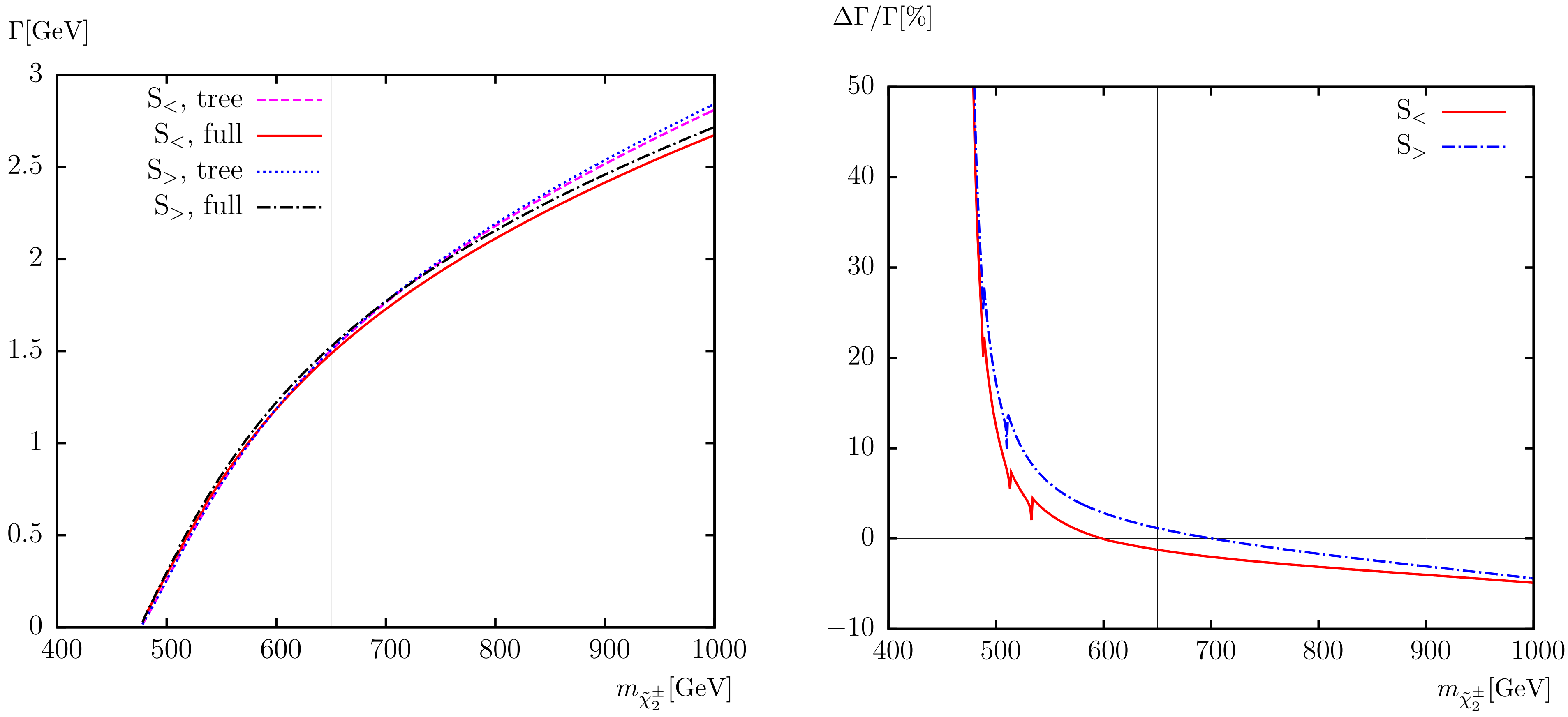


– including W^+–H^+ or G^+–H^+ transition contribution on the external Higgs boson leg

– including all soft/hard QED/QCD diagrams

$\Gamma(\tilde{\chi}_2^- \to \tilde{\chi}_1^- h_1)$: dependence on $m_{\tilde{\chi}_2^\pm}$

[S.H., F. v.d. Pahlen, C. Schappacher '11]

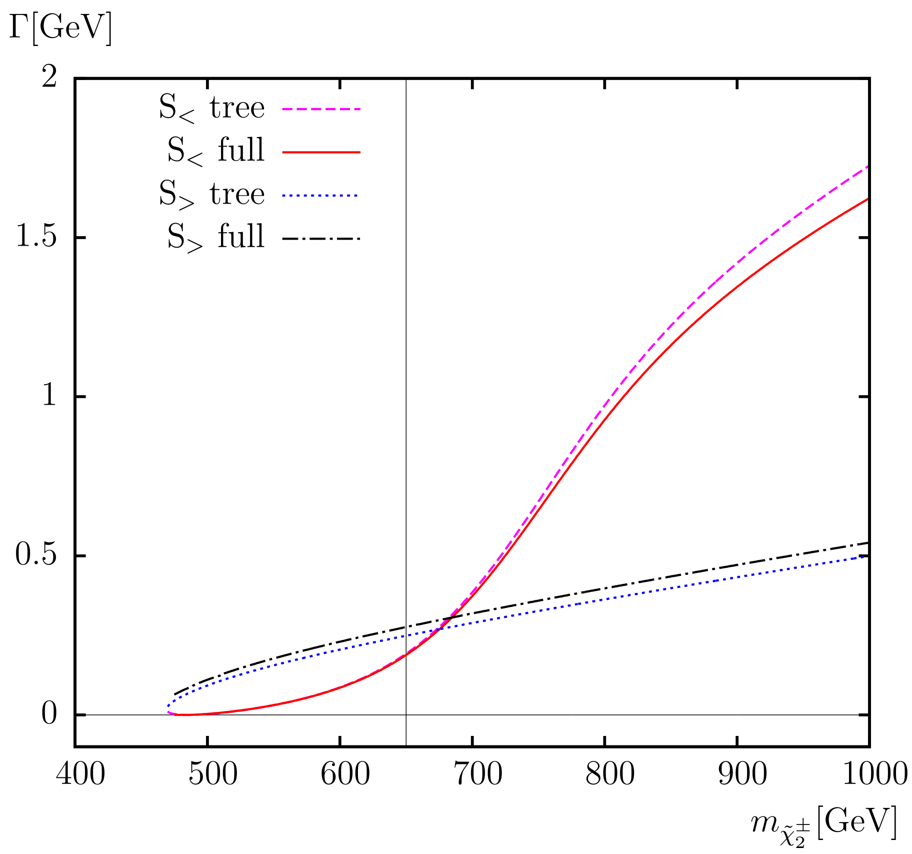


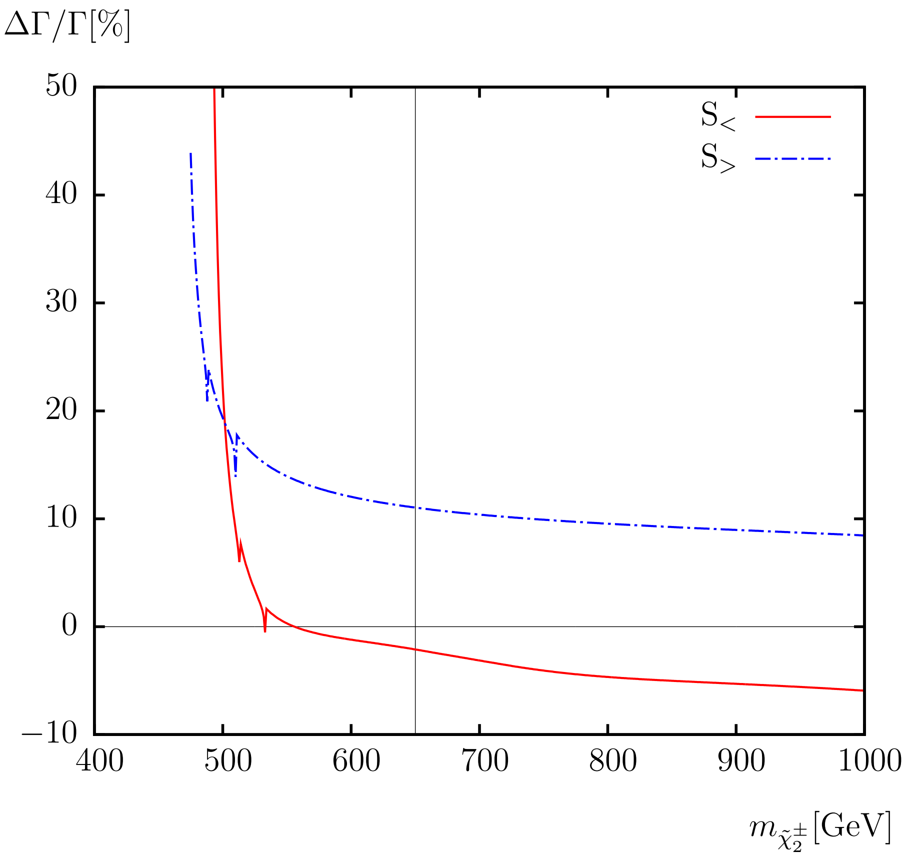
⇒ one-loop corrections under control and non-negligible

⇒ size of BR highly scenario dependent

$\Gamma(\tilde{\chi}_2^- \to \tilde{\chi}_1^0 H^-)$: dependence on $m_{\tilde{\chi}_2^\pm}$

[S.H., F. v.d. Pahlen, C. Schappacher '11]



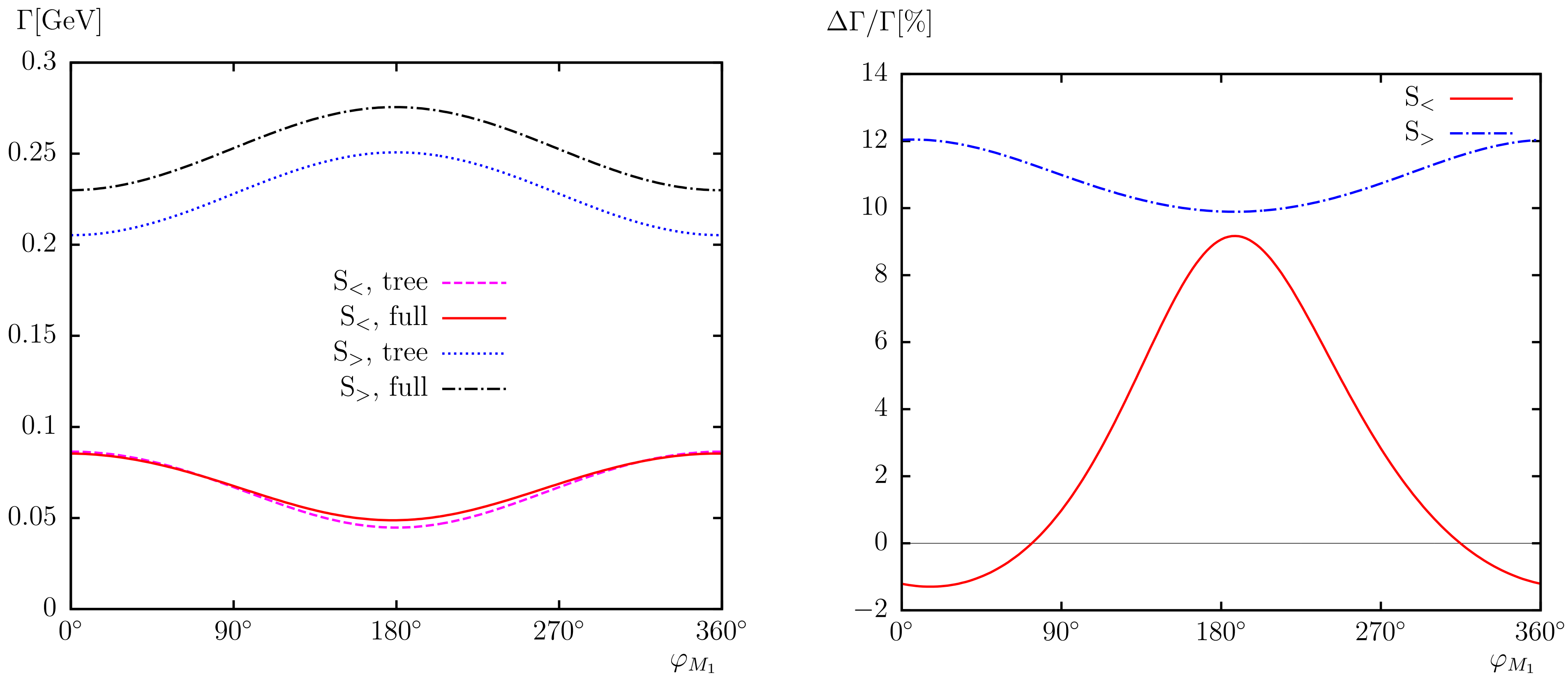


$\Rightarrow$ one-loop corrections under control and non-negligible

$\Rightarrow$ size of BR highly scenario dependent

$\Gamma(\tilde{\chi}_2^- \to \tilde{\chi}_1^0 H^-)$: dependence on φ_{M_2}

[S.H., F. v.d. Pahlen, C. Schappacher '11]



⇒ one-loop corrections under control and non-negligible

⇒ size of BR highly scenario dependent

4. Results for Dark Matter at the LC

Production of SUSY particles at the LC:

$$e^+e^- \to \tilde{t}_2\,\tilde{t}_1^\dagger \to h\,\tilde{t}_1\,\tilde{t}_1^\dagger \to h\,t\,\tilde{\chi}_1^0\,\bar{t}\,\tilde{\chi}_1^0$$

Possible: production of Higgs bosons: $\tilde{t}_2 \to \tilde{t}_1 h_i, \ldots$ $\Rightarrow$ light $\mathcal{CP}$-even Higgs

Always: production of the lightest SUSY particle: $\tilde{\chi}_1^0$ $\Rightarrow$ Dark Matter

$\Rightarrow$ important source for information on Higgs

$\Rightarrow$ important source for information on LSP/DM

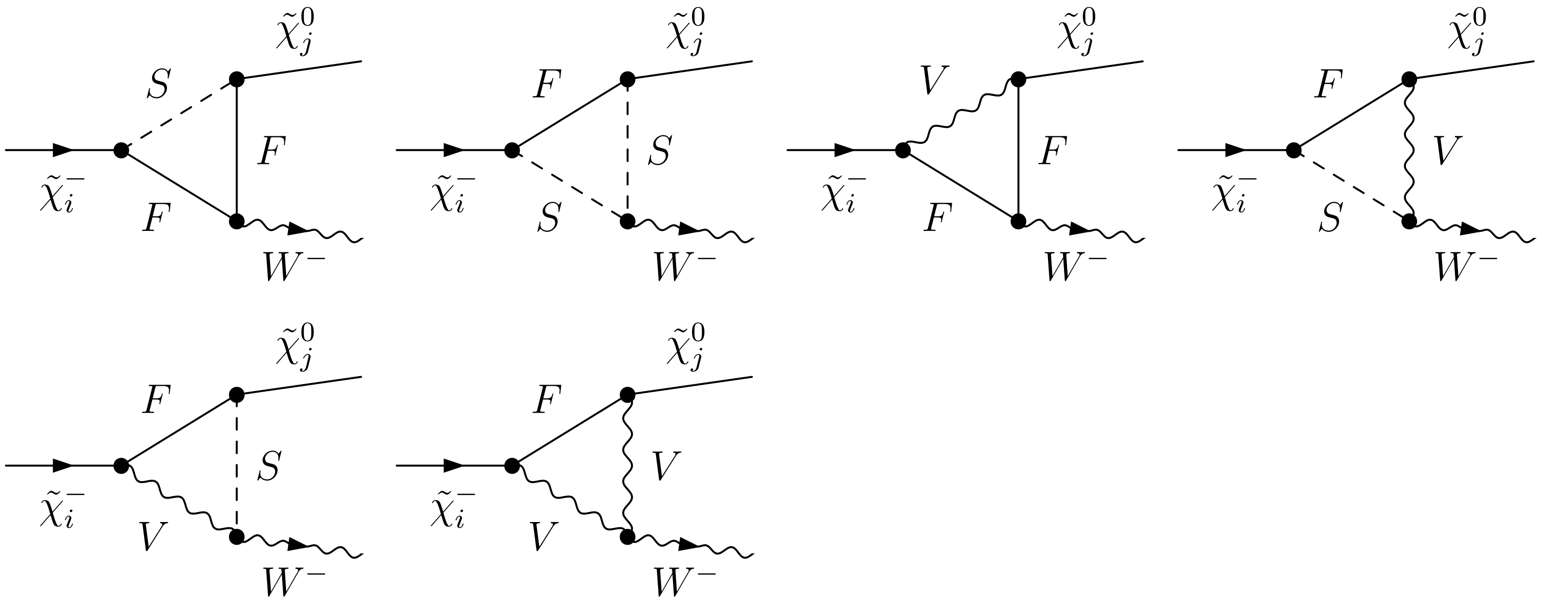
$\Rightarrow$ precision prediction (at least) of BR's necessary

4A) Chargino decays

$$\Gamma(\tilde{\chi}_2^\pm \to \tilde{\chi}_1^\pm h_k) \qquad (k = 1, 2, 3)\ ,$$
$$\Gamma(\tilde{\chi}_2^\pm \to \tilde{\chi}_1^\pm Z)\ ,$$
$$\Gamma(\tilde{\chi}_i^\pm \to \tilde{\chi}_j^0 H^\pm) \qquad (i = 1, 2,\ j = 1, 2, 3, 4)\ ,$$
$$\Gamma(\tilde{\chi}_i^\pm \to \tilde{\chi}_j^0 W^\pm) \qquad (i = 1, 2,\ j = 1, 2, 3, 4)\ ,$$
$$\Gamma(\tilde{\chi}_i^\pm \to \tilde{l}_k^\pm \nu_l) \qquad (i = 1, 2,\ l = e, \mu, \tau,\ k = 1, 2)\ ,$$
$$\Gamma(\tilde{\chi}_i^\pm \to \tilde{\nu}_l\, l^\pm) \qquad (i = 1, 2,\ l = e, \mu, \tau)\ .$$

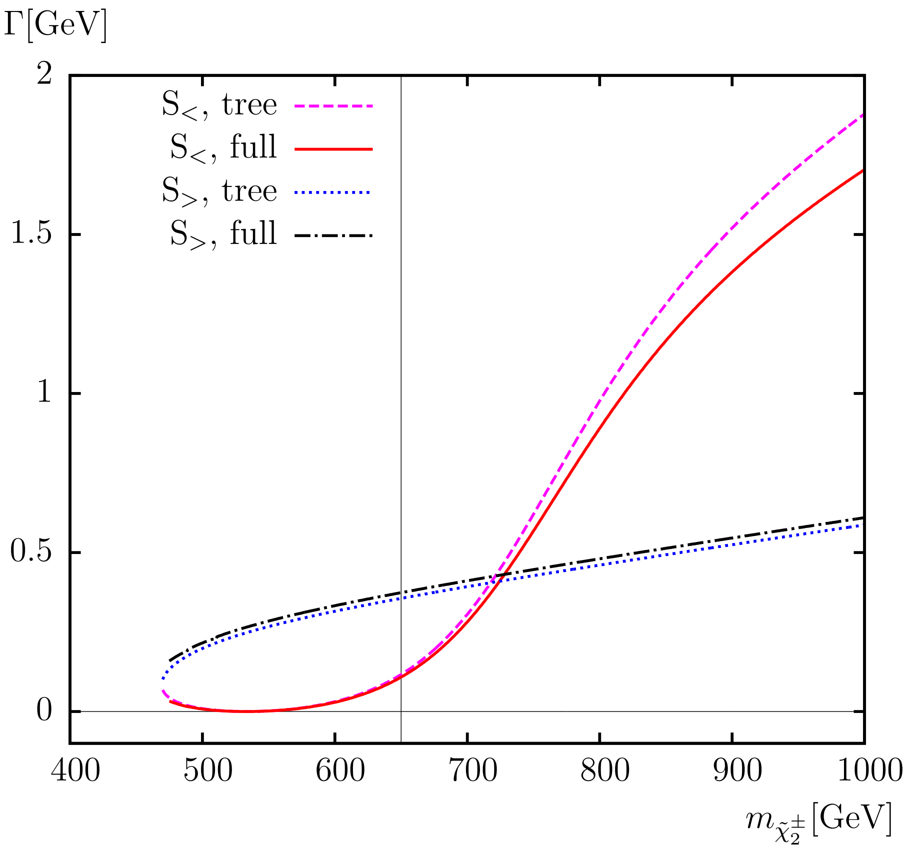
No hadronic decays yet . . .

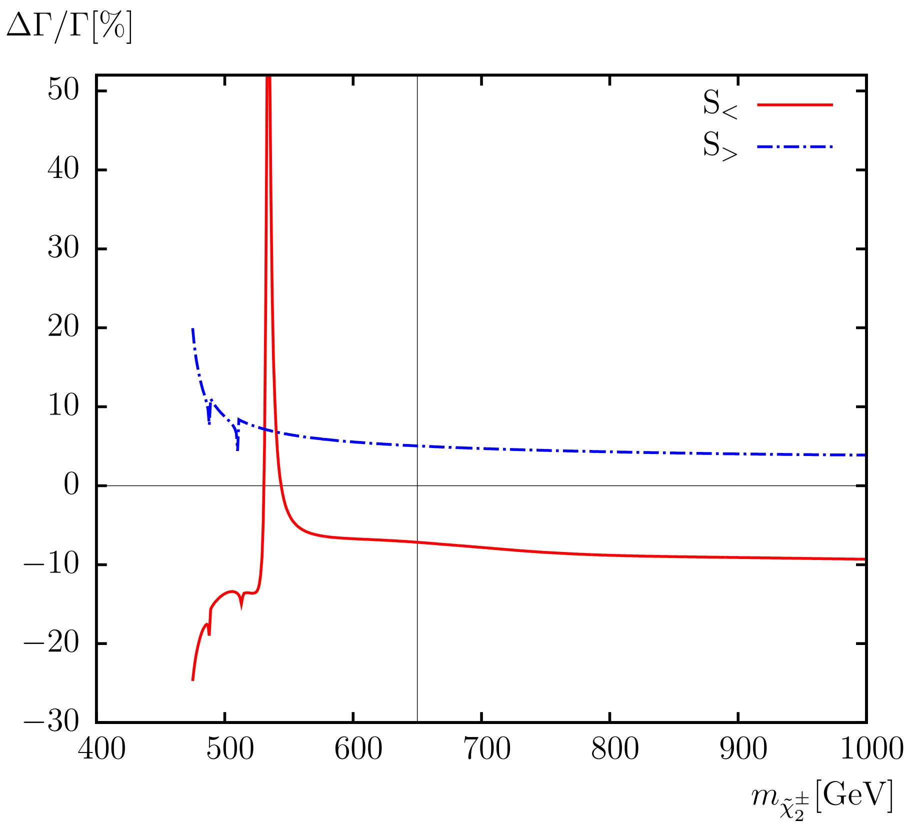
Feynman diagrams for $\tilde{\chi}_i^{\pm} \to \tilde{\chi}_j^0 W^{\pm}$



– including all soft/hard QED diagrams

$\Gamma(\tilde{\chi}_2^- \to \tilde{\chi}_1^0 W^-)$: dependence on $m_{\tilde{\chi}_2^\pm}$ [S.H., F. v.d. Pahlen, C. Schappacher '11]

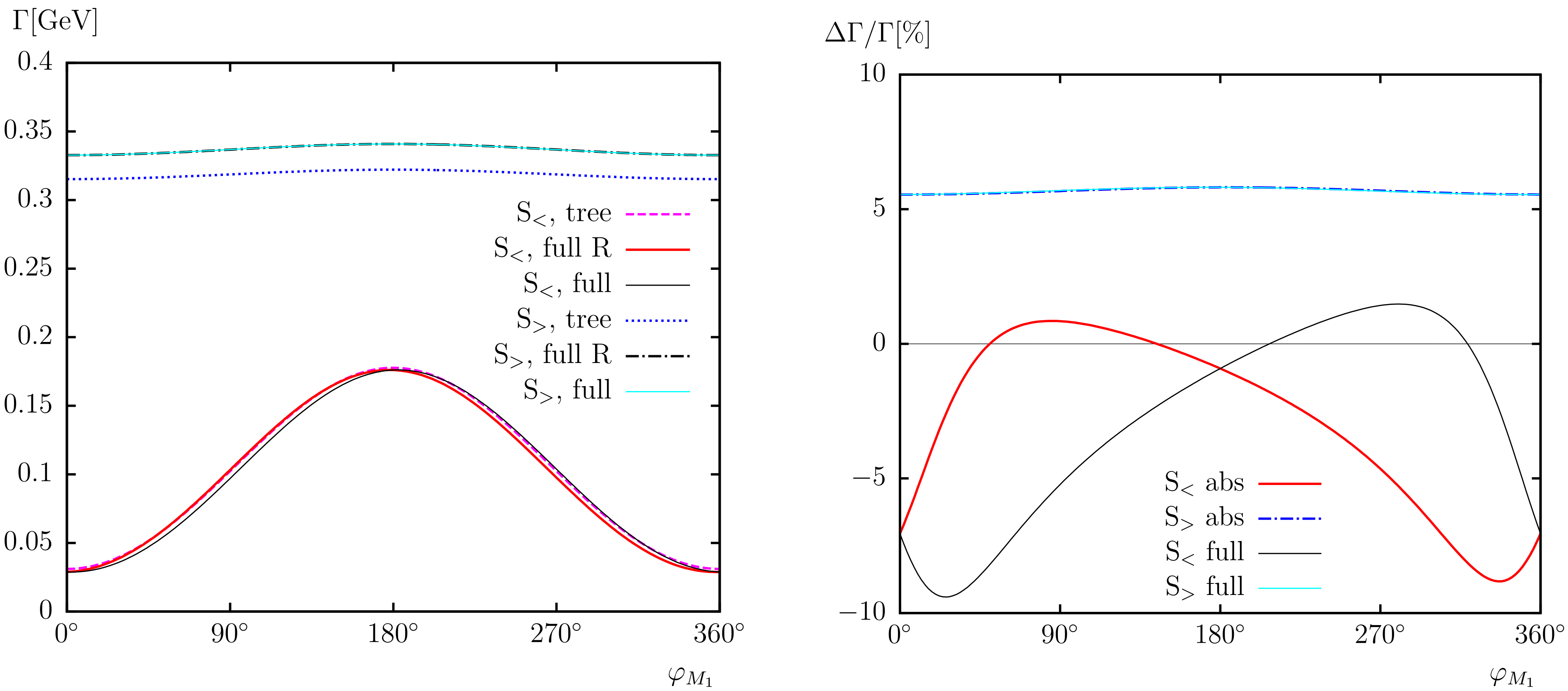




⇒ one-loop corrections under control and non-negligible

⇒ size of BR highly scenario dependent

$\Gamma(\tilde{\chi}_2^- \to \tilde{\chi}_1^0 W^-)$: dependence on φ_{M_1} [S.H., F. v.d. Pahlen, C. Schappacher '11]



⇒ one-loop corrections under control and non-negligible

⇒ size of BR highly scenario dependent

4B) Neutralino decays

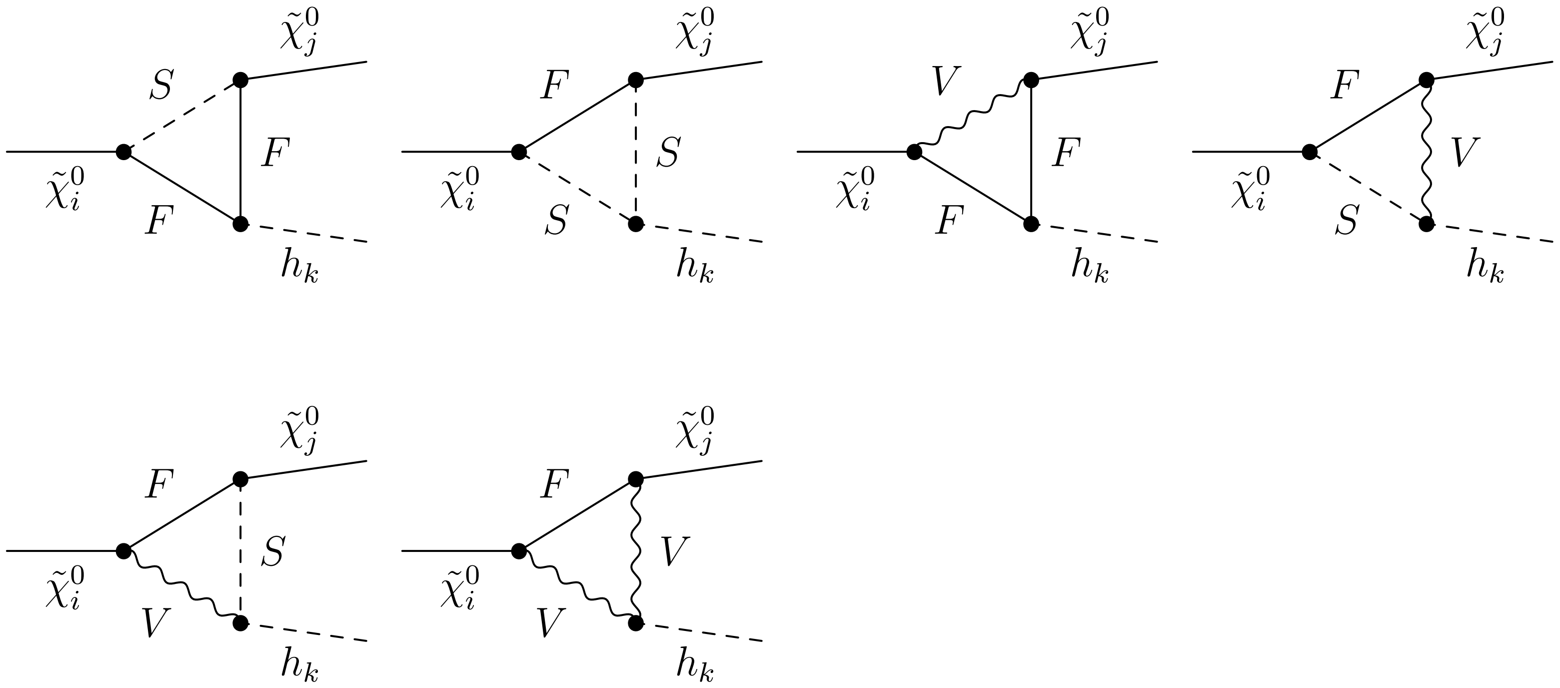
$$\Gamma(\tilde{\chi}_i^0 \to \tilde{\chi}_j^0 h_k) \qquad (i = 2,3,4;\ j < i;\ k = 1,2,3)\ ,$$
$$\Gamma(\tilde{\chi}_i^0 \to \tilde{\chi}_j^{\mp} H^{\pm}) \qquad (i = 2,3,4;\ j = 1,2)\ ,$$
$$\Gamma(\tilde{\chi}_i^0 \to \tilde{\chi}_j^{\mp} W^{\pm}) \qquad (i = 2,3,4;\ j = 1,2)\ ,$$
$$\Gamma(\tilde{\chi}_i^0 \to \tilde{\chi}_j^0 Z) \qquad (i = 2,3,4;\ j < i)\ ,$$
$$\Gamma(\tilde{\chi}_i^0 \to \ell^{\mp}\, \tilde{\ell}_k^{\pm}) \qquad (i = 2,3,4;\ \ell = e,\mu,\tau;\ k = 1,2)\ ,$$
$$\Gamma(\tilde{\chi}_i^0 \to \bar{\nu}_\ell\, \tilde{\nu}_\ell / \nu_\ell\, \tilde{\nu}_\ell^\dagger) \qquad (i = 2,3,4;\ \ell = e,\mu,\tau)\ .$$

No hadronic decays yet . . .

$\tan\beta$	$M_{H^\pm}$	$m_{\tilde{\chi}_2^\pm}$	$m_{\tilde{\chi}_1^\pm}$	$M_{\tilde{l}_L}$	$M_{\tilde{l}_R}$	A_l	$M_{\tilde{q}_L}$	$M_{\tilde{q}_R}$	A_q
20	160	600	350	300	310	400	1300	1100	2000

$$\mathcal{S}_h : \mu > M_2 \quad (\tilde{\chi}_4^0 \text{ more higgsino-like})$$
$$\mathcal{S}_g : \mu < M_2 \quad (\tilde{\chi}_4^0 \text{ more gaugino-like})$$

Feynman diagrams for $\tilde{\chi}^0_i \to \tilde{\chi}^0_j h_k$

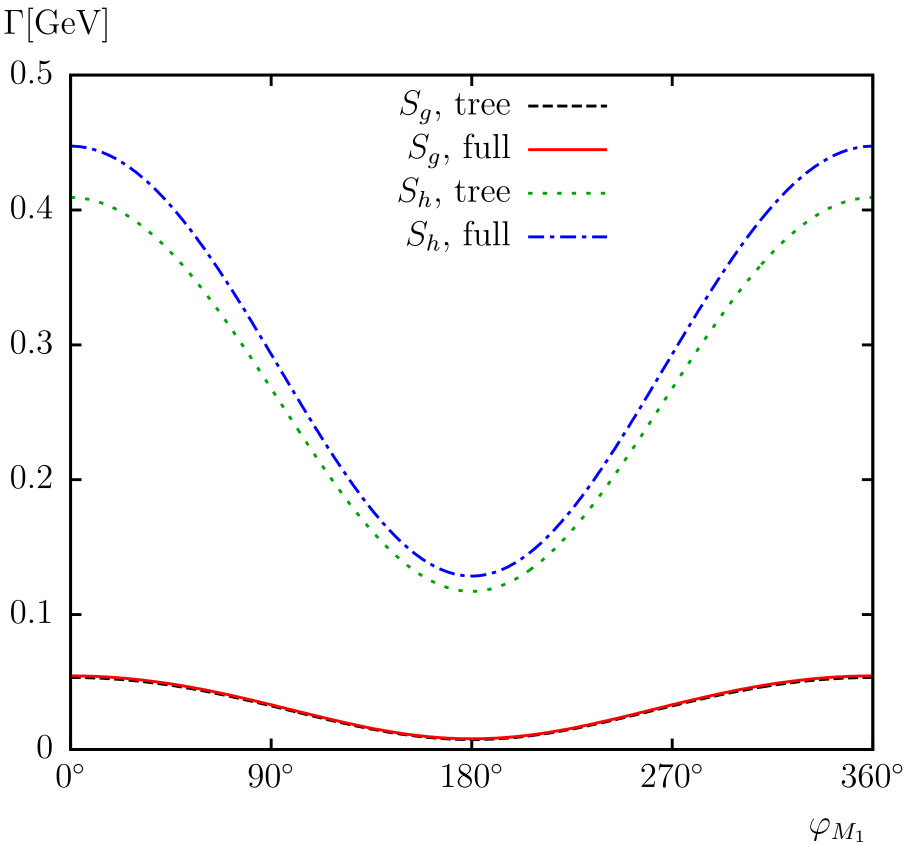


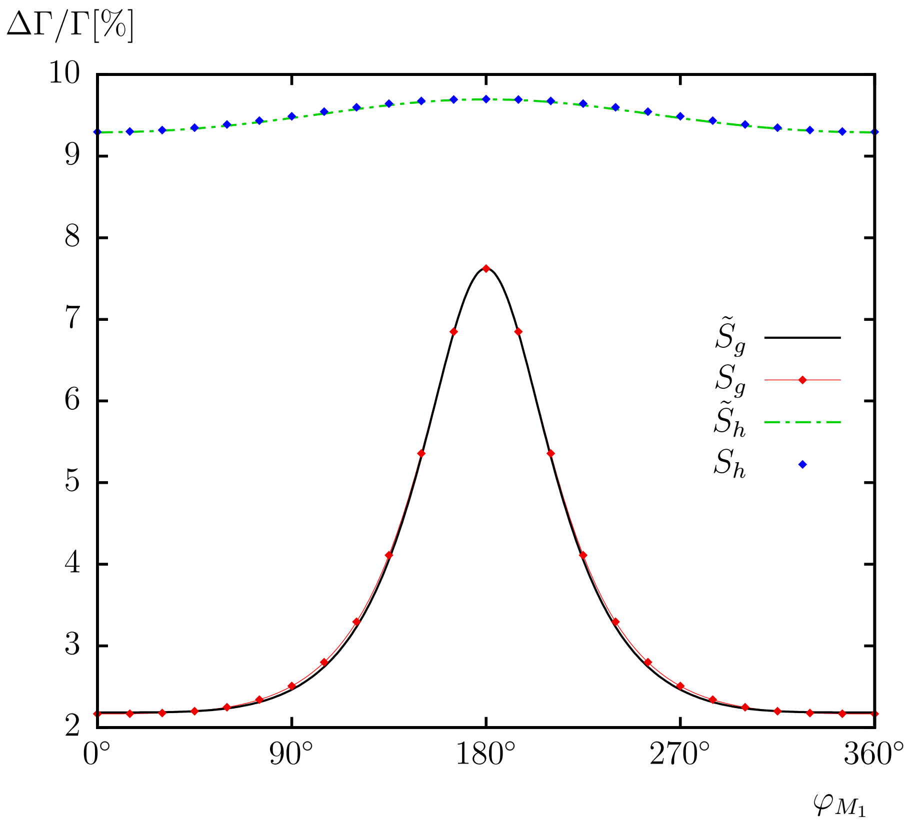
– including Z–A or G–A transition contribution on the external Higgs boson leg

– including all soft/hard QED diagrams

$\Gamma(\tilde{\chi}^0_4 \to \tilde{\chi}^0_1 h_1)$: dependence on φ_{M_1}

[A. Bharucha, S.H., F. v.d. Pahlen, C. Schappacher '12]





⇒ one-loop corrections under control and non-negligible

⇒ size of BR highly scenario dependent

5. Conclusinos

- The Higgs will be explored at the LC
  SUSY will be explored at the LC

- LC precision often is in the per-cent range
  ⇒ theory precision has to match!

  ⇒ many corrections still missing, in particular for Higgs

- Problem in the MSSM, in particular with complex parameters:
  consistent renormalization of the whole model (simultaneously)

  ⇒ now solved!
  ⇒ model file available for FeynArts/FormCalc/LoopTools

  ⇒ full one-loop calculations of any SUSY process possible

- (Updated) results available for:
  - Higgs boson masses
  - Higgs boson production cross sections
  - Higgs decays and decays to Higgs bosons
  - production of Dark Matter at the LC

- Always(?) more higher-order corr. necessary to match LC precision!